

LIMITED SCOPE REPORT

Advancing Best Practices for the Formulation of Localized Sea Level Rise/Coastal Inundation Extremes' Scenarios for Military Installations in the Pacific Islands

SERDP Project RC-2335

JULY 2015

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REPORT DOCUMENTATION PAGE				<i>Form Approved</i> OMB No. 0704-0188	
<small>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Executive Services and Communications Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</small>					
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1. REPORT DATE (DD-MM-YYYY) 14.07.2015		2. REPORT TYPE Final Limited Scope Report		3. DATES COVERED (From - To) February 2013- July 2015	
4. TITLE AND SUBTITLE Advancing Best Practices for the Formulation of Localized Sea Level Rise/Coastal Inundation "Extremes" Scenarios for Military Installations in the Pacific Islands				5a. CONTRACT NUMBER DG133W10CQ0042	
				5b. GRANT NUMBER NA11NMF4320128	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) John J. Marra, Mark A. Merrifield, and William Sweet				5d. PROJECT NUMBER 5RN3APC	
				5e. TASK NUMBER P00; P0H	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Department of Commerce NOAA NESDIS National Centers for Environmental Information 151 Patton Avenue, Asheville, NC 28801-5001				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Strategic Environmental Research and Development Program 4800 Mark Center Drive, Suite 17D03 Alexandria, VA 22350-3605				10. SPONSOR/MONITOR'S ACRONYM(S) SERDP	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) RC-2335	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT A series of analysis, along with a review of previous work and expert input on best practices, form the basis for the creation of guidance that outlines best practices and methodologies that can be used to formulate probabilistic estimates of extreme events under a changing climate for specific locations in the Pacific Islands. This includes the creation of innovative proof-of-concept products that can be used directly to support decision-making ranging from area-wide vulnerability assessment related to climate adaptation planning and disaster risk reduction to site-specific analysis related to design and maintenance of facilities and infrastructure at select Department of Defense sites.					
15. SUBJECT TERMS Sea level rise; coastal inundation; extreme value analysis; Pacific Islands.					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON John J. Marra
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include area code) 808.725.5974

**Advancing Best Practices for the Formulation of Localized Sea Level
Rise/Coastal Inundation "Extremes" Scenarios for Military Installations in
the Pacific Islands - RC-2335**

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List of Acronyms

AEP - Annual Exceedance Probability
AMR - Annual Median Removed
ARI - Average Recurrence Interval
BEST - Bivariate ENSO Time Series
CO-OPS - Center for Operational Oceanographic Products and Services
DoD - Department of Defense
EMI - El Niño Modoki
ENSO - El Niño Southern Oscillation
ESTCP - Environmental Security Technology Certification Program
EVA - Extreme Value Analysis
EWC - East-West Center
GCM - Global Climate Model
GEV - Generalized Extreme Value Distribution
GIS - Geographic Information System
GOW - Global Ocean Wave Model
GPD - Generalized Pareto Distribution
IT - Information Technology
JASL - Joint Archive for Sea Level
JIMAR - Joint Institute for Marine and Atmospheric Research
MSL - Mean Sea Level
NCAR - National Center for Atmospheric Research
NCDC - National Climatic Data Center
NCEP - National Centers for Environmental Prediction
NESDIS - National Environmental Satellite, Data, and Information Service
NOAA - National Oceanic and Atmospheric Administration
NOS - National Ocean Service
NTR - Non-Tidal Residual
ONI - Oceanic Niño Index
OBS - Observed Monthly Maxima
PDO - Pacific Decadal Oscillation
PNA - Pacific North American Teleconnection Index
POT - Peaks-Over-Threshold
RCP - Regional Concentration Pathways
SERDP - Strategic Environmental Research and Development Program
SLP - Sea Level Pressure
SOI - Southern Oscillation Index
SON - Statement of Need
SST - Sea Surface Temperature

SWL - Still Water Level

TW1 - Technical Workshop 1

TW2 - Technical Workshop 2

UH - University of Hawaii

UHSLC - University of Hawaii Sea Level Center

USACE - United States Army Corps of Engineers

USGS - United States Geological Survey

Keywords: Sea level rise; coastal inundation; extreme value analysis; Pacific Islands.

Acknowledgements

The project team is particularly indebted to Dr. Melisa Menéndez, Environmental Hydraulic Institute Universidad de Cantabria, and Ayesha Genz, Research Assistant, University of Hawaii Sea Level Center (UHSLC), whose contributions were critical to the success of this effort. Dr. Mendez spent several days on several occasions working with members of the project team, providing code, analyzing results and offering guidance and insights. Under supervision of the project team, Ayesha did the bulk of the data processing and re-processing leading to prototype product development. Special thanks go out to the group of technical experts who attended the workshop and gave a week of their time and energy in support of this effort. Their presentations and the group discussions were an invaluable contribution. Thanks also to the various colleagues in NOAA, at UH, and in the EWC who contributed to this effort, in particular Eric Wong for his time spent providing detailed copy edits. Finally, thank you to the DoD/SERDP for their financial support, and for their support, guidance, and patience along the way.

Abstract

Objective: A series of analysis, along with a review of previous work and expert input on best practices, form the basis for the creation of guidance that outlines best practices and methodologies that can be used to formulate scenario-dependent probabilistic estimates of future extreme sea levels under a changing climate for specific locations in the Pacific Islands. This includes the creation of innovative proof-of-concept products that can be used directly to support decision-making ranging from area-wide vulnerability assessment related to climate adaptation planning and disaster risk reduction to site-specific analysis related to design and maintenance of facilities and infrastructure at select Department of Defense (DoD) sites.

Technical Approach: Analysis of Pacific Island tide station records by previous workers has shown that extreme water levels primarily result from a combination of global and regional changes in mean sea level, El Niño Southern Oscillation (ENSO) and other modes of natural variability, tropical and extratropical storms, and unusually high tides. This suggests that in response to a changing climate, and in addition to increasing global sea level, alterations to natural patterns of sea level variability and storminess may contribute to the more frequent occurrence of extreme water level events. Analyses also show that the relative importance of the various contributors to extreme water levels varies from location to location. This suggests that changes in the frequency of occurrence of extreme water level events due to a changing climate may be highly localized. Potential limitations related to the sparseness of data (e.g., if the tide station record is of limited duration or if no station exists near a location of interest) represent another set of issues that needs to be accounted for.

A sequence of analyses using families of distributions –the Generalized Pareto Distribution (GPD) and the Generalized Extreme Value (GEV) – was conducted to address these issues. Here the focus is on a form of non-stationary extreme value analysis (EVA) using the GEV distribution fit to monthly maximum water levels. We allow the GEV location and scale parameters to vary in time, as temporal functions (linear, quadratic, exponential, and periodic) or covariates. Applied to tide station records at select sites, our approach enabled the extreme component of the water level signal to be decomposed into various components (e.g., tidal versus non-tidal, patterns versus trends) and be recombined in a way that more accurately reflects how the various contributors can combine to determine extreme water levels at a specific place and time. These analyses were reviewed and discussed at a technical workshop held in Honolulu, Hawaii on November 6 and 7, 2013, along with a number of other considerations related to best practices and methodologies that can be used to formulate probabilistic estimates of extreme water levels.

Results: The objective was successfully achieved. Methods were developed to create innovative proof-of-concept products that account for patterns of sea level variability and storminess as well as global and regional trends at specific locations in the Pacific Islands, and that can be used directly to support decision-making. The results confirm that considerable variation occurs from location to location with respect to which and to what extent various contributors are expressed. For most locations, the seasonal cycle and long-term trend account for the bulk of the low-frequency time-varying changes in extreme distribution (location parameter). For some locations, low frequency climate variability (i.e., elevated sea level anomalies) also was significant.

Influences of extra-tropical storms are significant seasonally (in scale parameter) at many locations and reveal long-term changes at a few locations. Tropical cyclone events are significant at some locations in terms of the overall characterization of the distribution reflective of its “shape” parameter. Methods similar to those applied to the formulation of the hindcast products created here have been applied elsewhere, but not in the Pacific Islands. Their application to the formulation of the forecast products created here is particularly novel. Further work is needed to complete the location specific diagnoses started here. Specifically isolating impacts that result from prolonged sea level anomalies (location parameter) and changes in typical (extratropical) storm track (scale parameter) need to be explored as does the applicability of customized climate indices.

Development of these methods, along with a review of previous work and expert input on best practices, formed the basis for the creation of guidance that can be used to formulate probabilistic estimates of extreme events under a changing climate for specific locations in the Pacific Islands and beyond—a primary goal of this effort. This work suggests that for a given setting the “best” approach to the formulation of probabilistic estimates of extreme events under a changing climate depends on a number of factors. Requirements framing, data reconnaissance, and data assembly are part of the scoping that needs to be carried out prior to data treatment and analysis. Depending on the outcome of the scoping process, one among a set of possible EVA method ‘cases’ may be most applicable for determination of the current extreme event probability. In all cases, a sea level trend and climate sensitivity analysis also needs to be conducted. The results of the various analyses are combined to create estimates of future extreme event likelihood in forms amenable to decision-making.

This work also has revealed that a tendency has been to focus on rare (high magnitude/low probability) inundation events. The behavior of more common (i.e., low magnitude/high probability) inundation events have only recently begun to receive attention. Because these “lesser” extremes (i.e., defined as <5 year event probabilities) are likely to have the greatest cumulative impacts over the coming decades, delineating their expression in a changing climate represents an area where future research and follow-on applications development is warranted.

Benefits: This project has advanced the practical application of extreme value analysis to inform decision and policy making as well as our basic understanding of the factors affecting sea level rise and coastal inundation. The DoD is now in a position to apply the results to improve their understanding of which components of DoD infrastructure are potentially vulnerable to sea level rise/coastal inundation and how they could be affected, as well as how species and ecosystems associated with DoD lands and waters will respond to sea level rise/coastal inundation. The results can (and have been) incorporated into location and region-specific tools and models. In this regard, efforts have been carried out to transfer these results to other on-going Strategic Environmental Research and Development Program (SERDP) projects (i.e., Storlazzi et al.). This project has expanded the capacity to communicate the risks of sea level rise/coastal inundation, and more broadly the impacts of climate change and climate variability. The results, both the location specific products and the more general best practices guidance, have broad applicability within the region and the nation. As noted above, this project also has served to identify issues and opportunities for future work that will further enhance the enhance DoD’s ability to understand and predict the potential impacts of sea level rise and coastal inundation under a changing climate.

Objective

The objective of this project is to develop guidance that outlines best practices and methodologies that can be used to formulate location-specific probabilistic estimates of extreme events under a changing climate and apply it to select Department of Defense (DoD) sites in the Pacific Islands. Formulation of innovative approaches to extreme value analysis and their proof-of-concept application is complementary to several Strategic Environmental Research and Development Program (SERDP) supported projects, and will add to the set of tools that DoD decision makers and the scientific community use to identify vulnerable assets, assess impacts, and determine appropriate adaptive responses to sea-level rise and associated phenomena. As such, it is consistent with the objectives outlined in the Statement of Need (RCSON-13-01- DOD Pacific Island Installations: Impacts of and Adaptive Responses to Climate Change) in that the work will lead to an improved understanding of potential impacts of climate change and climate variability, including extreme events, on resources of relevance to the DoD in the Pacific Island region and beyond. Though it addresses several of the specified research needs, it is perhaps most relevant to research need number 1. – *Potential impacts of climate change on military infrastructure that result from coastal flooding and erosion, as well as loss of protective wetlands and other coastal ecosystems serving that function.*

At a primary level the research is applied in nature, targeted at advancing the practical application of extreme value analysis to inform decision and policy making. Specifically, it addresses the following questions:

- 1) How can extreme value analysis and other statistical techniques be used and what approaches are best suited to account for variability in patterns of sea level variability and storminess as well as global and regional trends?
- 2) How can extreme value analysis and other statistical techniques be used and what approaches are best suited to account for differences that exist from location to location in terms of the relative importance of various contributors to extremes?
- 3) How are the various approaches to extreme value analysis constrained by data limitations, related to the sparseness of data (e.g., sea level station records may be of limited duration or there is no station near a location of interest), and how might they be combined with statistical or other techniques to overcome these limitations?

There are also aspects of the research that are more basic in nature, focused on advancing our understanding of the factors affecting sea level rise and coastal inundation. Here, relevant questions include:

- 1) What is the relative importance of the various contributors to extreme water levels at particular locations?
- 2) How might these various contributors be expected to change with a changing climate and, in turn, how would these changes be expressed in term of changes in the magnitude and frequency of extreme water level events?

To a considerable extent, work carried out under this project successfully achieved its objectives. In particular, it met the stated goal of limited scope projects by generating data and information needed to develop a more extensive follow-on project. The time varying EVA methods used here were able to detect how various contributors – patterns of sea level variability and

storminess as well as global and regional trends – have uniquely combined to determine extreme water levels at specific locations. This has laid the groundwork for further diagnosis and prognosis. It has revealed, for example, the need for additional sensitivity analysis with respect to location, scale, shape parameters as well as exploration of the applicability of customized climate indices. The time varying EVA complemented the primary objective of this effort, the development of guidance that outlines best practices and methodologies that can be used to formulate probabilistic estimates of extreme events under a changing climate. Together with the review of previous work and expert input on best practices that formed the basis for the guidance, it helped to highlight the importance of more common inundation events and identify these “lesser” extremes (i.e., defined as <5 year event probabilities) as an area warranting future research and follow-on applications development. The project also confirmed limitations with respect to tide station data and products, and the need to explore other data sources to complement and extend the results achieved here and, in a variety of ways, make them more amenable to practical applications.

Background

Elevated water levels result from the complex interplay of a spectrum of oceanic, atmospheric, and terrestrial processes (Figure 1). Analysis of Pacific Island tide station records show that extreme water levels primarily result from a combination of global and regional changes in mean sea level; El Niño Southern Oscillation (ENSO) and other modes of natural variability; tropical and extratropical storms; and unusually high tides (e.g., Firing et al., 2004; Cayan et al., 2008; Menéndez and Woodworth, 2010; Chowdhury et al., 2010; Woodworth et al., 2011; Marra et al.,

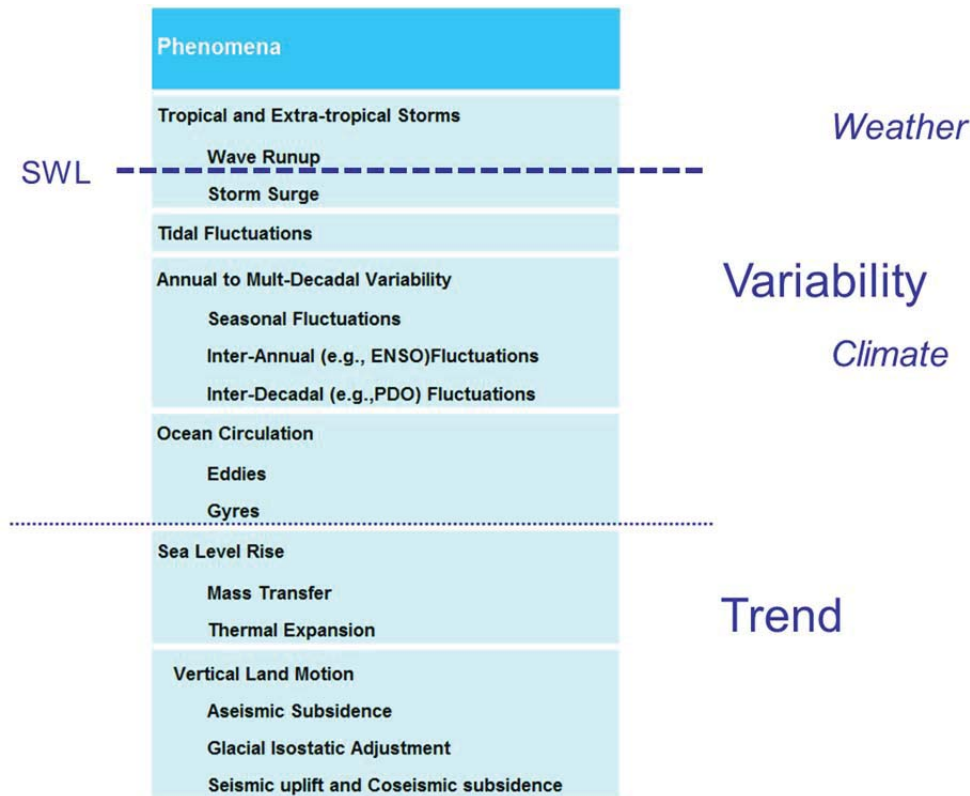


Figure 1. Factors Affecting Extreme Water Levels in the Pacific Islands (after Marra et al., 2012). *In the Pacific Islands extreme water levels primarily result from a combination of global and regional changes in mean sea level due to the addition of mass and density changes driven by processes operating over centuries to millennia; ENSO and other modes of natural variability that control regional to local mean sea level over decades to months; tropical and extratropical storms, and swell from distant storms that manifest as events lasting hours to seconds; unusually high tides; and regional to local vertical land motion. Here, these factors are partitioned for the purpose of analysis. They are generally representative of a Still Water Level (SWL) due to tide station design, sampling protocols and harbor location which tend to exclude the highest frequencies associated with wave runup (setup plus swash). Higher frequency processes are treated as Variability, and further subdivided into Tidal versus Non-Tidal Residual (NTR), where the NTR contains weather-related components associated with tropical and extratropical cyclones and climate-related components associated with seasonal variability, ENSO, etc. Lower frequency processes are treated as Trends. In practice exactly where the “line” between trends or variability sits depends on the perspective of interest (space and time frames).*

2012; Merrifield et al., 2013). This suggests that in response to a changing climate, and in addition to increasing global sea level, alterations to natural patterns of sea level variability and storminess may contribute to the more frequent occurrence of extreme water level events. The tide station analyses also show that the relative importance of the various contributors to extreme water levels varies from location to location (e.g., Merrifield et al., 2007; Menéndez and Woodworth, 2010; Woodworth et al., 2011; Marra et al., 2012; Merrifield et al., 2013). This suggests that changes in the frequency of occurrence of extreme water level events due to a changing climate may be highly localized. The challenge is to understand and predict how these processes combine to manifest as extreme sea levels (aka Still Water Level, SWL) at specific places and times, now and in the future (Marra et al., 2007).

The prediction of the probability of exceeding a certain extreme sea level is useful for assessing current and future risk exposure (Marbaix and Nicholls, 2007; Obeysekera and Park, 2013), and employing various types of Extreme Value Analysis (EVA) to estimate extreme sea levels from tide station records is common practice (e.g., Coles, 2001; FEMA, 2005). *Direct* methods represent the simplest, most widely applied approach to EVA. In one direct method, the Generalized Extreme Value (GEV) distribution is used to compute the extreme value statistical distributions. In the GEV three parameters are used to characterize the distribution: a location parameter (μ) that specifies where the distribution is centered, a scale parameter (σ) which represents the dispersion and a shape parameter (ξ) that determines the shape of the upper tail of the distribution, with $\xi > 0$, $\xi < 0$, and $\xi = 0$ defining Fréchet, Weibull, and Gumbel members of the GEV family respectively (Figure 2). Block maxima is the method used by the GEV, and it can be annual or monthly and usually depends upon the desired outcomes (e.g., for insights into seasonal or climatic variability). Most common is the Annual Maxima Method (AMM), where the GEV distribution is fitted to the sea-level annual maxima (Figure 2). In another direct method, Peaks-Over-Threshold (POT), the Generalized Pareto Distribution (GPD) is fitted to all values above a certain threshold, with $\xi > 0$, $\xi < 0$, and $\xi = 0$ defining Pareto, Beta, and members of the GPD family respectively. With respect to which data is selected to fit by the distribution, the selection of peaks over a high threshold (e.g., 95%) provides a more intuitive approach to extreme analysis, allowing for multiple extremes in some years and none in others (Figure 3).

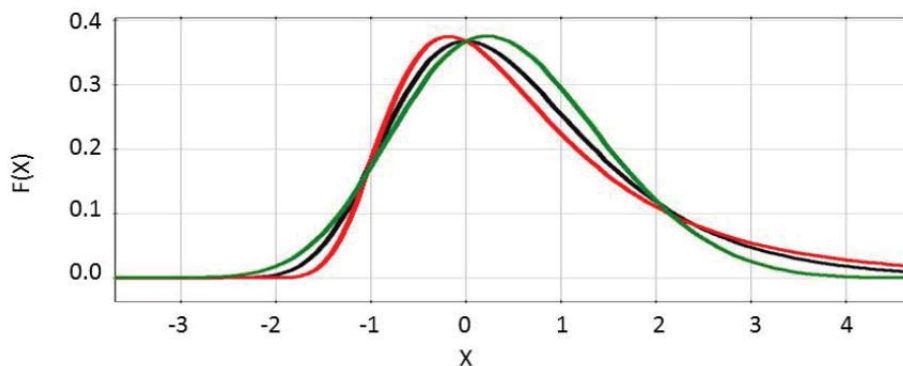


Figure 2. Generalized Extreme Value (GEV) probability distribution functions with a location parameter of 0 and a scale parameter of 1 (from Zervas, 2013). The shape parameters are -0.2 for the green curve (Weibull distribution), 0 for the black curve (Gumbel distribution), and 0.2 for the red curve (Fréchet distribution).

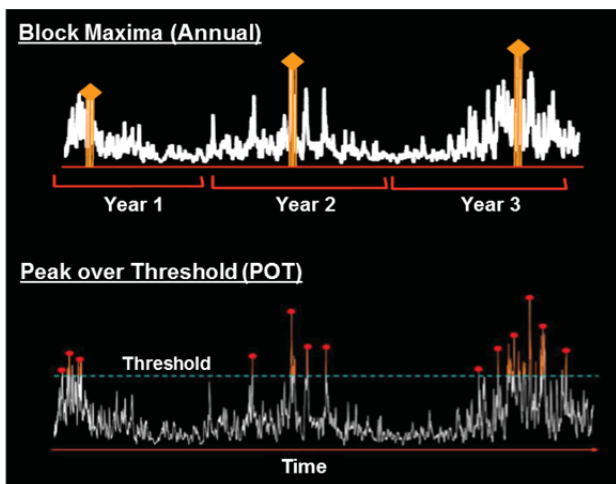


Figure 3. Schematic showing how extreme events are quantified by the two GEV-based extreme event analysis methods.

Note how the AMM GEV samples one event occurrence each year, whereas the POT GPD samples multiple event occurrences each year capturing two similarly sized events occur within one year and no occurrences the following year. Modification of figure in Menéndez, 2012.

The tendency has been to conduct EVA that can describe the ‘current’ extreme event probability. While useful for establishing the characteristics of the distribution, the applicability of stationary forms of EVA are limited by their inability to account for any changes in distribution characteristics over time. Investigators have recently begun to incorporate elements into EVA to address nonstationarity. Simpler forms of analysis, using the GEV approach for example, allow the location parameter to vary linearly with time as a means to account for observed or predicted trends (e.g., Thompson et al., 2009; Hunter, 2010; Ruggiero et al., 2010; Tebaldi et al., 2012; Kruk, et al., 2013; Obeysekera and Park 2013). More sophisticated forms of GEV analyses employ statistics that allow the parameters to be temporal functions (i.e., linear, quadratic, exponential, and periodic) or covariates (e.g., Mendez et al., 2007; Menendez et al., 2009; Menendez and Woodworth, 2010). This allows the extreme sea level signal (tail of its distribution) to be decomposed into its various components and describe how the characteristics of the extremes distribution changes with time as a result of both patterns and trends. This approach is considered in detail within the next section.

Limitations with respect to the calculation of exceedance probabilities of extreme water levels from tide station records are well recognized (e.g., Coles, 2001; FEMA, 2005; McInnes et al., 2009; Thompson et al., 2009; Haigh et al., 2013a; Haigh et al., 2013b). They center on the issue of the extent to which any given station record is truly representative; for example, of sufficient length and, in particular, a length to accurately capture low probability events attributable to tropical cyclones. Related to this is the extent to which the geographic distribution of tide stations is sufficient to provide an accurate spatial representation of extreme probabilities. Considering that there are only about 20 tide stations in the Western and Central Pacific (excluding Japan and Taiwan) and that only about half of these have 30 or more years of data, these issues present a challenge and warrant attention with respect to the application of EVA in the Pacific Islands.

Materials and Methods

Technical Workshops: The work carried out under this project follows on and builds upon a history of work, including a precursor technical workshop held in Honolulu, Hawaii on January 10th and 11th, 2012 ([TW1](#)). One outcome of the first workshop was the adoption of a conceptual framework amenable to generation of specific products using extreme value analysis and other statistical techniques, as well as the formulation of general guidance. This involved an idealized partitioning of the various factors identified in Figure 1, where

Formula 1)

$$SWL = \int_{\text{function of } [Variability (Tide + NTR_{\text{weather}} + NTR_{\text{climate}}), MSL \text{ Trend}]}$$

and SWL is the Still Water Level, the sea level excluding wave runup (setup plus swash). The Tide is the astronomical Tide; NTR is the Non-Tidal Residual which contains weather-related components associated with storm and other ocean-atmospheric processes (e.g., tropical and extratropical cyclones) and climate-related components associated with associated with seasonal to inter-decadal variability (e.g., ENSO, PDO, etc.) – all treated as ‘variability’. The Mean Sea Level (MSL) is treated as a ‘trend’. This conceptual framework is consistent with others found in the literature (e.g., Pugh, 1987; Pugh, 2004; Haigh et al., 2010; Haigh et al., 2013a; Haigh et al., 2013b; Merrifield et al., 2013).

Another outcome of the first workshop was a round of EVA and product development based in part on recommendations made at the workshop ([P1](#)). As part of these precursor analyses, EVA of three tide stations in the Pacific Islands were carried out to evaluate the robustness of solutions in terms of sensitivity of the GPD and GEV to record length. The results of these analyses as well as those described below were incorporated into the best practices Guidance document that accompanies this report.

As part of this DoD-funded effort, a second technical workshop was held in Honolulu, Hawaii on November 6 and 7, 2013 ([TW2](#)). This workshop brought together almost 30 experts from around the world to: 1) share knowledge and explore our current understanding of factors affecting extreme water levels in the Pacific Islands; and 2) solicit input on best practices and methodologies that can serve as guidance for the development of probabilistic estimates of extreme water levels. The conceptual framework noted above was introduced at the outset of the meeting, as was a strawman for best practices guidance based on three levels of analysis, each of increasing complexity in terms of inputs, analysis, and outputs. This strawman was used to structure presentations and discussions, which included a review of the analyses and product development work described below. In addition to the objectives noted above, participants were asked to consider the implications of the discussions to product requirements for decision-makers and to needs for future research.

Together, the expert input on best practices from both workshops, two rounds of EVA analysis and product development (the latter described below and in Appendix A), and broad literature review, formed the basis for the creation of guidance that can be used to formulate probabilistic estimates of extreme events under a changing climate for specific locations in the Pacific Islands and beyond. The Practitioners Guidance is a separate, stand-alone document that accompanies

this report. This combination of efforts also helped to shape the Research Plan outlined in Appendix B.

Hindcast and Forecast Products: As part of this effort, both prior and subsequent to the second technical workshop, a sequence of analyses was conducted using a time-dependent GEV distribution of the form (after Mendez et al., 2007; Menendez et al., 2009; Menendez and Woodworth, 2010).

Formula 2)

$$G(z, \theta) = \left\{ \exp \left\{ - \left[1 + \xi \left(\frac{z - \mu(t)}{\psi(t)} \right) \right]^{-1/\xi} \right\} \right\} \quad \psi(t) > 0$$

$$\theta = (\mu(t), \psi(t), \xi)$$

As noted above, the model has three parameters: a location parameter – mu (μ) that specifies where the distribution is centered, a scale parameter - psi (ψ) which represents the dispersion and a shape parameter – Xi (ξ) that determines the shape of the upper tail of the distribution.

Here, the tide station data is decomposed specifically as follows:

- a. Location: $\mu(t) = \beta_0 + \mu_S(t) + \mu_P(t) + \mu_N(t) + \beta_{LT}t + \beta_{CLI}CLI$
 $\mu_S(t) = \beta_0 + \beta_1 \cos(\omega t) + \beta_2 \sin(\omega t) + \beta_3 \cos(2\omega t) + \beta_4 \sin(2\omega t)$
 $\mu_P(t) = \beta_{P_1} \cos(\omega_P t) + \beta_{P_2} \sin(\omega_P t)$
 $\mu_N(t) = \beta_{N_1} \cos(\omega_N t) + \beta_{N_2} \sin(\omega_N t)$
- b. Scale: $\psi(t) = \alpha_0 + \psi_S(t) + \alpha_{LT}t$
 $\psi_S(t) = \alpha_0 + \alpha_1 \cos(\omega t) + \alpha_2 \sin(\omega t) + \alpha_3 \cos(2\omega t) + \alpha_4 \sin(2\omega t)$
- c. Shape: (ξ) is constant

where $\omega = 2\pi/T$, and $T=1$ year; $\omega_P = 2\pi/T_P$, and $T_P = 4.4$ years; and $\omega_N = 2\pi/T_N$, and $T_N = 18.61$ years. The sub-index S is for Seasonality, P is for Perigean tide cycle, N is for Nodal tide cycle, LT is for long-term trend, and CLI is for climate variability. The shape parameter is held constant ($\xi = \gamma_0$).

Thus location and scale parameters represent nonstationary components in the model – nonstationary including cycles (e.g., intra-annul seasonal-related to interannual long term tidal-related), patterns (linked to climate-related indices), and trends (found in the maximums and that generally are the same trend value as the MSL).

This model was applied to 15 Joint Archive for Sea Level (JASL) tide stations within the Pacific Basin (Table 1; Figure 4). The hourly time series data for these stations were acquired from the University of Hawaii Sea Level Center (UHSLC) Research Quality database and extended through December 2011 using the UHSLC Fast Delivery database.

Table 1. Pacific Island Tide Stations Selected for Analysis.

Station #	Location		Start Year	End Year	# Years
014a	French Frigate	USA	1974	2011	38
028b	Saipan	N. Mariana Islands	1978	2011	34
050a	Midway	USA Trust	1947	2011	65
051a	Wake	USA Trust	1950	2011	62
052a	Johnston	USA Trust	1947	2011	65
053a	Guam	USA Trust	1948	2011	64
055a	Kwajalein	Rep. of Marshall I	1946	2011	66
056a	Pago Pago	USA Trust	1948	2011	64
057b	Honolulu	USA	1905	2011	107
058a	Nawiliwili	USA	1954	2011	58
059a	Kahului	USA	1950	2011	62
060a	Hilo	USA	1927	2011	85
061a	Mokuoloe	USA	1957	2011	55
355a	Naha	Japan	1966	2011	46
552a	Kawaihae	USA	1989	2011	23

Note that prior to analysis data treatment was conducted to ensure that, with the exception of Kawaihae, these stations had at least 30 years of data, 80% complete, and 80% coverage between 1983 and 2001.

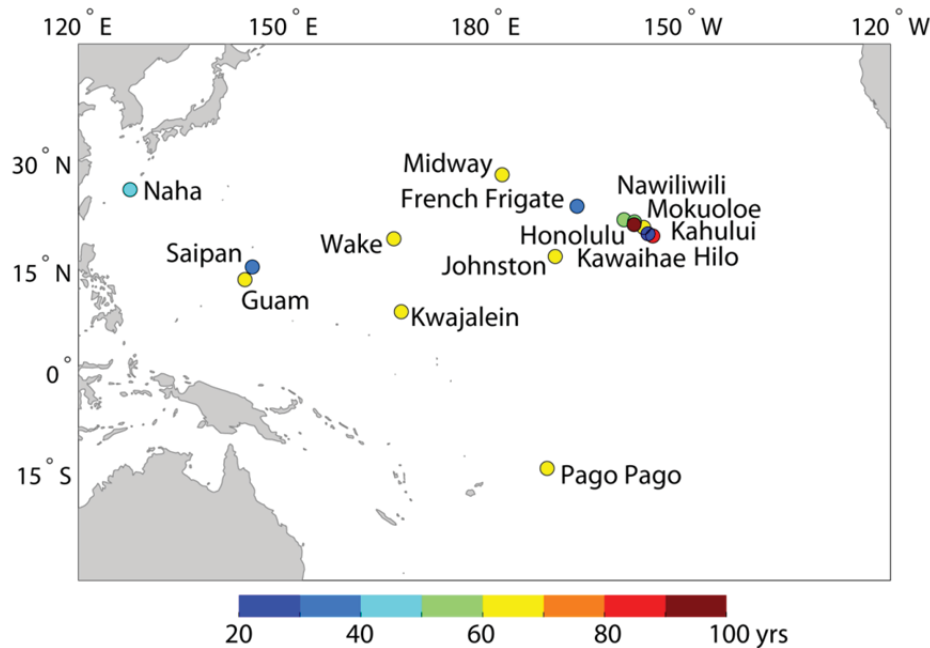


Figure 4. Map showing the location of Pacific Island Tide Stations Selected for Analysis.
Colored legend depicts length of the individual tide station records.

Runs were made on Observed Monthly Maxima (OBS) and monthly maxima with the annual median removed (AMR) time series. The Annual Median Removed (AMR) takes the monthly maximum water levels (observed heights based off of hourly data) and subtracts the median value of that calendar year from the 12 monthly values. This removes much of the low frequency variation. The OBS method is simply the observed monthly maximum water levels with no data treatment. Changes in extreme water levels that are separate from Mean Sea Level (MSL) are better identified with AMR than with OBS. However, the AMR method also removes a portion of the underlying low-frequency climate variability signal; thus the OBS time series was used for product development.

Models were tested in a stepwise manner – starting with the simplest model and then adding parameters at each step. The maximum likelihood ratio test (90th percentile) is used to determine the model that has the least amount of parameters that best describes the data.

There were a total of 6 GEV runs for each station. The first run excludes a climate index parameter (β_{CLI}) in the location parameter. For all other runs, the location parameter includes the climate index term. Five climate indices are tested: BEST, EMI, ONI, PDO, PNA (Figure 5).

- The Bivariate ENSO Time Series (BEST) combines a standardized Southern Oscillation Index (SOI) (atmosphere) with a standardized Niño 3.4 (oceanic) Sea Surface Temperature (SST) (Smith and Sardeshmukh, 2000). We use the 5-month running mean dataset.
- The El Niño Modoki (EMI) is similar to El Niño, but focuses on the warming in the Central Pacific and cooling in the Eastern and Western Pacific (Ashok et al., 2007). EMI is the second mode of the SST anomalies.
- The Oceanic Niño Index (ONI) is the 3-month running mean of Niño 3.4 SST (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml).
- The Pacific Decadal Oscillation (PDO) is developed from the leading principal component of SST anomalies (e.g., Zhang et al., 1997; Mantua et al., 1997).
- The Pacific North American teleconnection index (PNA) describes the atmospheric circulation and teleconnection patterns (<http://www.cpc.ncep.noaa.gov/data/teledoc/pna.shtml>).

Further detail on individual indices can be found at the links provided. Note that additional climate indices were tested on French Frigate and Guam stations in an initial round of analysis as a basis for selection of the 5 ultimately used for product development. Those selected were found to be the best mix of indices to capture a range of atmospheric and /or oceanic variability.

Custom climate indices were used on Midway (Global Ocean Wave (GOW) Model) and the Main Hawaiian Islands (Sea Level Pressure (SLP) from NCEP/NCAR reanalysis). Midway has known wave setup (Aucan et al., 2012) so we explored to what extent we could find an

appropriate covariate to quantify the response. The GOW elicited by far the largest water level response in the extreme space. The Hawaiian Islands have little response to any climate index and so we attempted to create our own for water level. We did this using NCEP/NCAR reanalysis to identify what parameter and its spatial extent that had the greatest correlation with monthly maximum water levels. In this case it was atmospheric sea level pressure and its pattern time series was used in the extreme model and found to have the highest effect upon past extreme water levels and their probabilities.

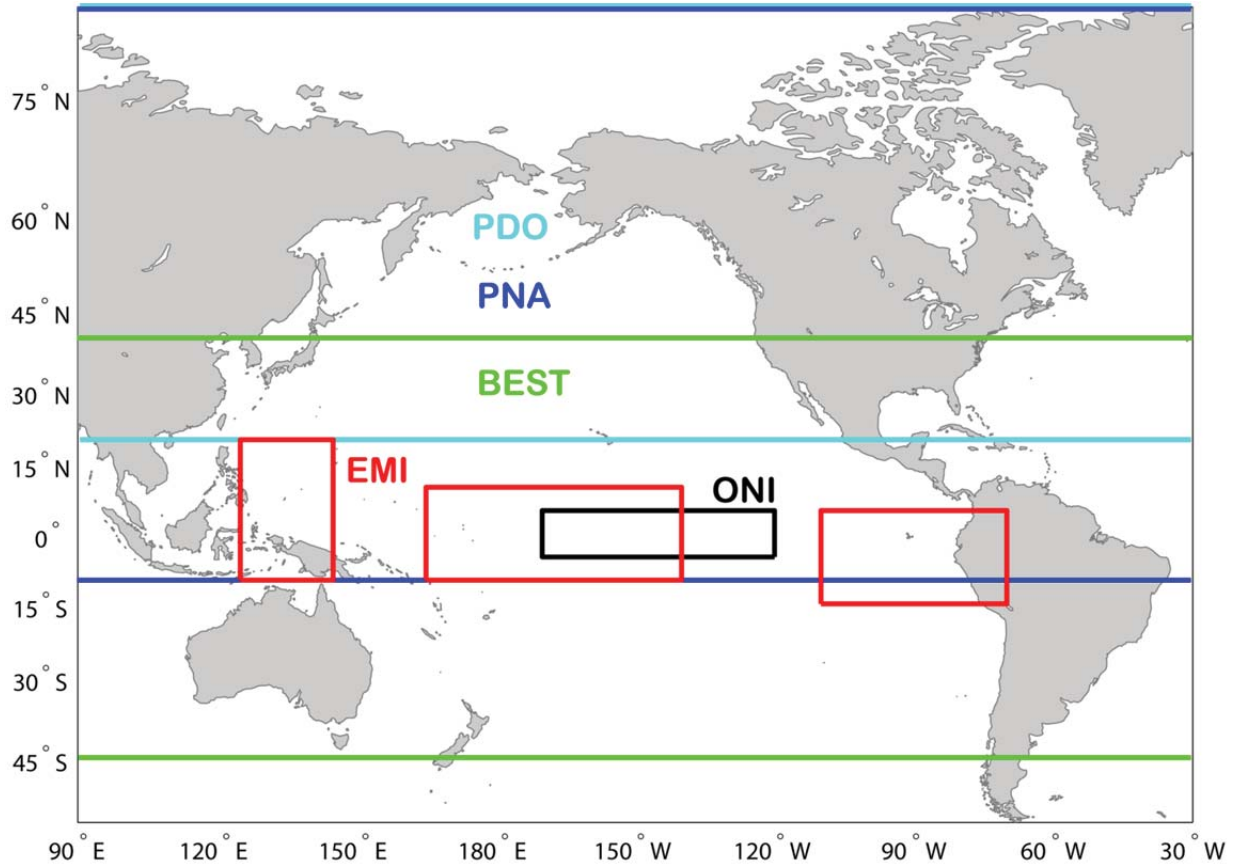


Figure 5. Spatial Domain of the Five Climate Indices tested in the time-varying GEV runs. *Bivariate ENSO Time Series (BEST), El Niño Modoki (EMI), Oceanic Niño Index (ONI), Pacific Decadal Oscillation (PDO), and Pacific North American teleconnection index (PNA).*

Ultimately, two sets of products were generated: 1) Hindcast products that incorporate the variability of seasonal, astronomical, long-term trend, and climate indices components from the historical data; 2) Forecast products that use the seasonal and astronomical components from the historical data and add future sea-level rise estimated trends (i.e., Parris et al., 2012) to predict future return levels; and 3) Forecast products that use the climate indices components to predict the range in future return levels associated with different phases of natural variability.

Additional details on the analysis procedure used to create the proof-of-concept hindcast and forecast products presented here and discussed further below can be found in Appendix A. In

addition to the product plots, this Appendix includes a tabular summary of the results of all runs at each station. Each station has a separate sheet, which includes the terms and standard error for the location, scale and shape parameters. The amplitudes and percent variances for each significant term are also included for each station. The Guidance document that accompanies this report provides further information on ways in which estimates of future extreme event likelihood can be developed and delivered through the type of analysis considered above.

The future sea-level rise estimated trends of Parris et al. (2012) noted above refer to the global mean sea level rise scenarios developed for the 2013 US National Climate Assessment (NCA). Note that semi-empirical approaches are factored into these projections of global means, and trends in ocean dynamics and geoid changes that may affect extreme scenarios on a regional basis are not accounted for. Further details on these scenarios can be found in Parris et al. (2012) and the Guidance Document.

Results and Discussion

Extreme Value Analysis: Figure 6 presents a synthesis of the results of the analysis described above. It shows the percent variance of the location parameter attributable to non-climate (i.e., long term tidal and seasonal components), long term (trends), and climate components for each of the 15 stations selected for analysis for both OBS and AMR runs. The climate index that encompasses the greatest percentage of variance for each station is shown, with the indices from the standard set in bold and custom indices in regular text. Also shown (as γ) is an indicator of the ratio of importance of high tide to high water levels (e.g., ~5-yr event; Merrifield et al., 2013). When $\gamma=1$, the high water levels are determined by the tide. As γ increases, non-tidal components have greater influence on the high water levels.

	Non-Climate	Long-term	Climate	Index	γ	
OBS	French Frigate			NINO12	1.6	Percent Variance of the total location parameter <div> <div></div> = 0 - 1% <div></div> = 1 - 10% <div></div> = 10 - 25% <div></div> = 25 - 50% <div></div> = 50 - 90% <div></div> ➤ 90% </div>
	Saipan			ONI	1.0	
	Midway			GOW	2.2	
	Wake			BEST	1.3	
	Johnston			PNA	1.4	
	Guam			ONI	0.9	
	Kwajalein			ONI	1.1	
	Pago Pago			ONI	1.0	
	Honolulu			SLP	1.3	
	Nawiliwili			SLP	1.4	
	Kahului			SLP	1.2	
	Hilo			SLP	1.3	
	Mokuoloe			SLP	1.2	
	Naha			PDO	1.0	
	Kawaihae			SLP	1.3	
AMR	French Frigate	0.0009 m/yr			1.6	
	Saipan			PNA	1.0	
	Midway			GOW	2.2	
	Wake				1.3	
	Johnston			BEST	1.4	
	Guam			ONI	0.9	
	Kwajalein			ONI	1.1	
	Pago Pago			ONI	1.0	
	Honolulu	0.0003 m/yr		SLP	1.3	
	Nawiliwili			SLP	1.4	
	Kahului			SLP	1.2	
	Hilo			SLP	1.3	
	Mokuoloe			SLP	1.2	
	Naha				1.0	
	Kawaihae				1.3	

Note: white blanks imply that the model found no significant results

Figure 6. Decomposition of the Location Parameter within the Extreme Distributions in Pacific Island Tide Station Records. *The non-climate contributors to the location parameter are 1) seasonal (μ_S) and 2) nodal (μ_N) and perigean μ_P tidal components. The long term contributors is the trend (β_{LT}) and the climate contributors are BEST, EMI, ONI, PDO, PNA.SLP or GOW; γ is an indicator of the ratio of high tide to high water levels (Merrifield et al., 2013). Note that the value of γ for Guam suggests that the station record used in the analysis occurred over a period through which there was an anomalously low mean sea level. See text for details.*

Overall the results show that there is considerable variation from location to location with respect to which and to what extent various contributors are expressed, confirming similar observations reported by previous investigators (e.g., Firing et al., 2004, Merrifield et al., 2007; Cayan et al., 2008; Chowdbury et al., 2010; Menéndez and Woodworth, 2010; Woodworth et al., 2011; Marra et.al., 2012; Merrifield et al., 2013). They also demonstrate the ability of the time-varying GEV approach used here to detect how various contributors have uniquely combined to determine extreme water levels at specific locations.

Focusing on the results of the OBS runs it is apparent that for most locations, seasonal (and to a lesser extent) tidal variability account for the bulk of the variance in the extreme distribution. Thus intra-annual variability is typically larger than interannual variability, generally reflecting the often-large cycle in local MSL (location parameter) and/or stormy season (shape parameter not necessarily in-phase with the MSL cycle). In this regard, Johnston and Naha are noteworthy. For some locations, climate variability related to prolonged sea level anomalies is a major contributor (e.g., ONI and Guam, Kwajelin, Saipan). The custom indices at the Hawaiian Islands and Midway were found to describe significant covariability with unique forcings (i.e., SLP within a spatial footprint and/or the wave field/GOW) reflecting seasonal forcing patterns affecting high and low water stands. The climate indices with the highest percent variance contribution to the location parameter for each station are shown in Figure 7.

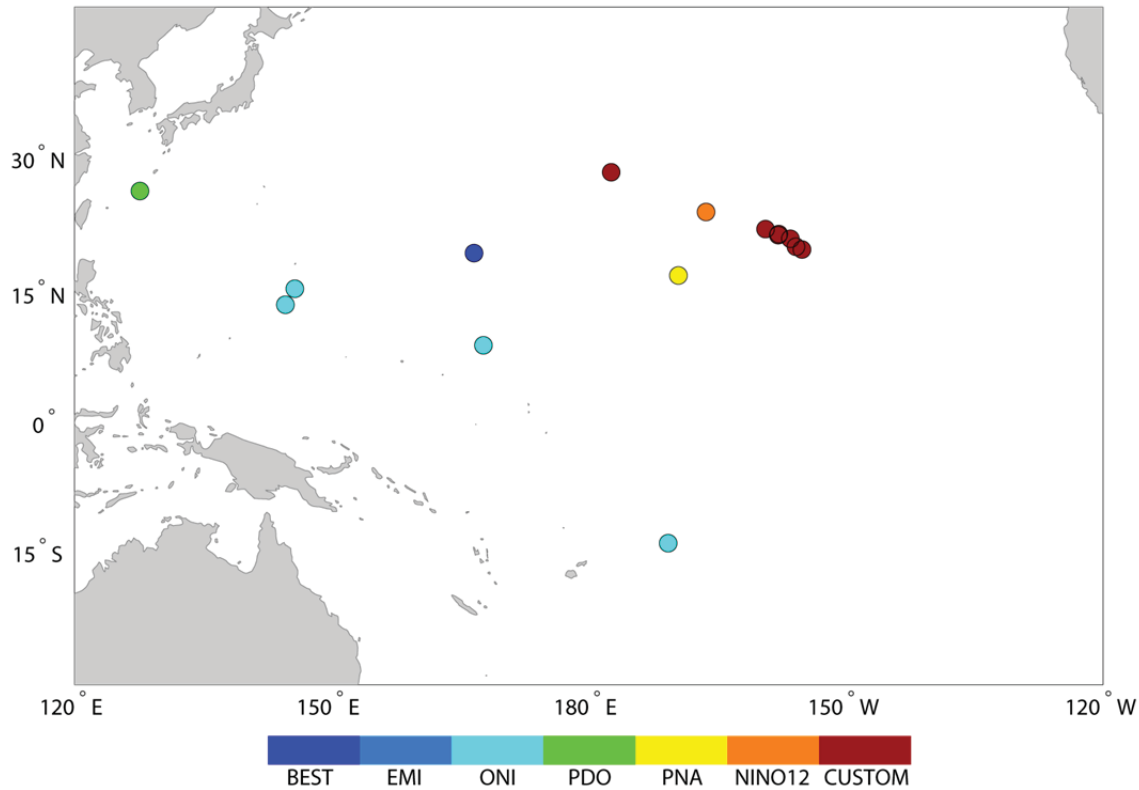


Figure 7. Climate indices with the highest percent variance contribution to the location parameter for each station in the OBS runs. *Note the grouping of stations in the southwest Pacific associated with the ONI and the grouping in the Hawaiian Archipelago associated with a custom (SLP) index. See text for details.*

Figure 6 also shows that trends in extreme levels tend to follow trends in MSL, because there are no trends in the extremes in addition to the MSL trends. This confirms similar observations reported by previous investigators (e.g., Woodworth and Blackman, 2004; Merrifield et al., 2007; Menéndez and Woodworth, 2010; Woodworth et al., 2011; Obeysekera et al., 2011, Tebaldi, et al., 2012; Marra et al., 2012; IPCC, 2013). The only exceptions to this were French Frigate and Honolulu, which had minor trends in their extremes in addition to their MSL trend. With respect to the relative importance of trends in MSL, Hilo and Pago and Pago are noteworthy with the former reflecting higher rates of vertical land motion and the latter also experiencing a likely datum shift from a localized earthquake in September of 2009.

With respect to the shape parameter, OBS and AMR runs have similar shape values at each station, the observed range shown in Figure 8. In all cases, the shape parameters are negative, which indicates no substantial outliers, or extremely rare high-magnitude, low-probability events. This is common for the Pacific region, as tide station locations are generally sheltered from typical typhoon tracks, direct landfalls are extremely infrequent, and the narrow continental shelves inhibit significant storm surge build-up from occurring.

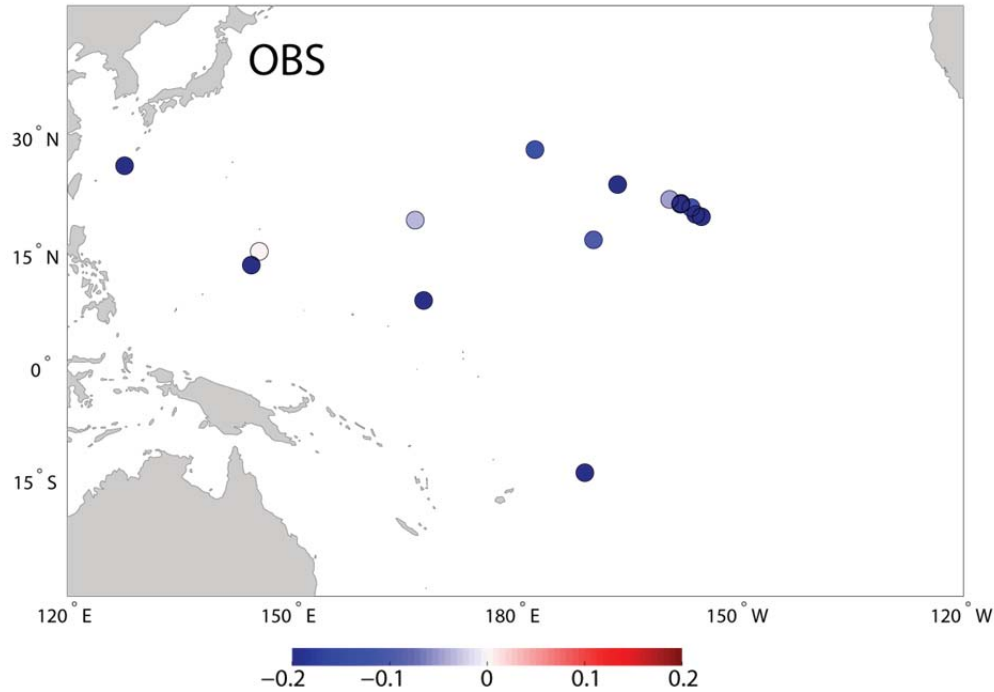


Figure 8. Value of the shape parameter for each station in the OBS runs. *Note that all values are negative. See text for details.*

Reflecting on these observations, our results appear to offer additional insights with respect to the statement that extreme sea level trends in tide station records tend to match trends in local mean sea level. The statement can be expected to hold in the future for settings where extremes are tidally dominated – which is most cases. In such settings tides will ride the rising seas, resulting in an increased frequency in extreme events (e.g., Merrifield and Firing, 2004; Cayan et al., 2008; Hunter, 2012; Sweet et al., 2014). In our study, we find that while extremes trends appear to parallel MSL trends, there exists significant climate-pattern variability such that a given year may have a substantially higher (or lower) probability of experiencing an extreme event. In essence, climatic forcing emulates a kind of response we see by the MSL cycle and induces significant (~ 0.25 m) intra-annual oscillation in the location parameter. The extent to which extreme trends will simply track mean sea level trends in storm-dominated settings is an open question. In settings dominated by tropical cyclones (i.e., storm surge), and probably more so in those where extremes are dominated by extra-tropical storms, a key issue is whether and how storm tracks and intensities are expected to change under future warming scenarios (as well as modes of variability for that matter). IPCC 2013 provides a nice review of studies that have addressed this issue and the related issue of the relative importance of changes in MSL versus storminess on the future expression of extremes. Results are mixed, with projected changes in extremes due to changes in storminess typically on the order of ± 0.1 m (e.g., Harper et al., 2009; McInnes et al., 2011; Colberg and McInnes, 2012) and in some cases much higher (0.5-3 m) (e.g., Unnikrishnan et al., 2011; Smith et al., 2010). Overall, recent assessments of future extreme conditions generally place low confidence on region-specific projections of future storminess (e.g., Seneviratne et al., 2012; IPCC, 2013). At least in settings where extremes are dominated by tropical cyclones, and thus truly extreme and rare, the issue of the relative importance of changes in MSL versus storminess on the future expression of extremes may be

moot. Here, relatively small changes in sea level even added up over long time periods are not expected to register as a significant change in event magnitude or frequency (with respect to these truly extreme events). The shape parameter is inherently nonstationary, meaning that every rare event will impact its value and with more rare events recorded, the more positive it becomes as does the return level estimate of the low probability events (e.g., 100-yr event) whose magnitude can be on the order of meters. If robust estimates of the extremely rare event are the end goal of an EVA, other methods besides direct statistical methods are warranted. In this regard, note that Regional Frequency Analysis (RFA) has proved highly successful for other regions (e.g., Bardet et al. 2011) and is an observational-based approach to obtain a more robust “shape parameter” estimate that puts outliers into a better perspective (probability wise).

In terms of changes in storminess due to changing storm tracks of extratropical storms, the scale parameter might (preliminary findings are supportive) show sensitivity to particular climate covariates similar to what we have explored thus far using the location parameter, which showed how prolonged changes in sea level (i.e., sea level anomalies) tend to covary in time. The result of a high scale parameter value is to increase the slope of a typical return interval curve and thus its time-varying parameterization might provide a “storminess envelope”. Further investigation is warranted to explore the past behavior of the scale parameter and project it forward.

Hindcast and Forecast Products: The ability of the time varying EVA methods to detect how various contributors – patterns of sea level variability and storminess as well as global and regional trends – have uniquely combined to determine extreme water levels at specific locations evident in Figure 6 is illustrated in finer detail via the suite of proof-of concept station hindcast products. There are simply too many (90+) to go through each one; however examples from Guam and Honolulu described below serve as cases in point.

Figures 9a (Guam) and 9b (Honolulu) show the contribution of each factor to the location parameter; S is for Seasonality, P is for Perigean tide cycle, N is for Nodal tide cycle, LT is for long-term trend, and CLI is for climate variability and the shape parameter is held constant ($\xi = \gamma_0$). In both Figures, the integrated sum of each component’s contribution to the location parameter is shown at the top in black (scale in meters). The amplitude of each factor is shown in centimeters and identified in text. Tide station ‘diagnosis’ plots similar to Figures 9a and 9b have been created before (e.g., Menendez et al., 2009), but not for Pacific Island stations.

For Guam (Figure 9a) the Perigean cycle is significant, the Nodal cycle is not. Seasonality is also significant (10.5cm), but much smaller than the climate parameter, ONI, which is the most significant contributor at 27.2cm. While variability on the order of a foot is impressive, this result is not surprising considering the strong sensitivity to the ENSO signal for many stations in the west equatorial Pacific. Still, it’s a quite important finding – that the probability of impacts during El Niño is substantially increased (and can be quantified). The long-term trend is also significant over the period of record.

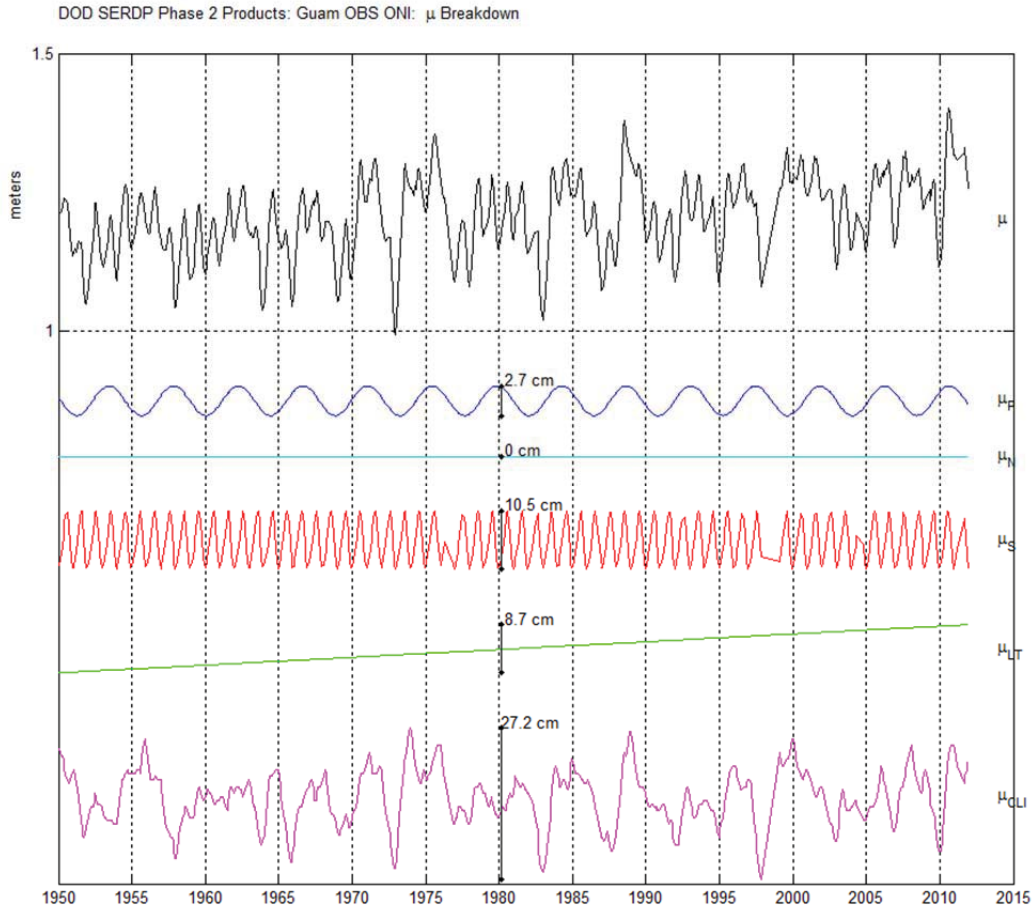


Figure 9a. Diagnosis of Guam station's historical extreme response. Example is of location parameter from an OBS run using ONI over the period 1948-2011. The black line is the integrated sum of each component's contribution to the location parameter. The dark blue line the Perigean and the light blue line the Nodal tide cycles respectively. The red line is the seasonal signal. The green line is the long-term trend. The magenta line is the climate index, ONI. The amplitude of each factor is shown in centimeters and identified in text. See text for details.

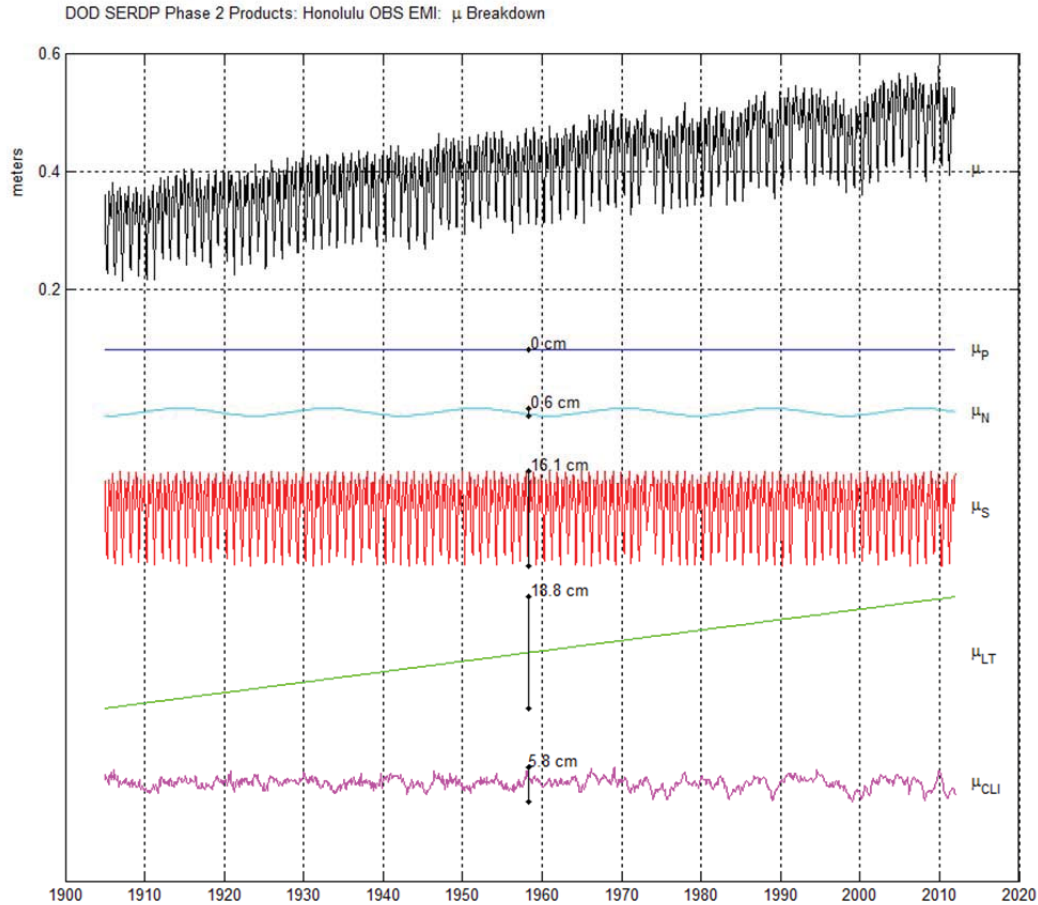


Figure 9b. Diagnosis of Honolulu tide station’s historical extreme response. *Example is of location parameter from an OBS run using EMI over the period 1905-2011. The black line is the integrated sum of each component’s contribution to the location parameter. The dark blue line the Perigean and the light blue line the Nodal tide cycles respectively. The red line is the seasonal signal. The green line is the long-term trend. The magenta line is the climate index, EMI. The amplitude of each factor is shown in centimeters and identified in text. See text for details.*

For Honolulu (Figure 9b) the Nodal cycle has a minor influence and Perigean cycle is not significant. Seasonality is significant (16.1cm), and much larger than the most significant climate parameter, EMI, at 5.8cm. This is consistent with the highest correlation of extremes to an SLP index, noted above, and is probably indicative of the role extra-tropical storms play in shaping the extremes distribution at this location. The long-term trend is also significant over the period of record, and as noted previously there is a long-term trend in the extreme above the MSL trend. This too may be indicative of the role of extra-tropical storms, and may reflect a change in storminess over the course of the record. It might also be an artifact of channel deepening in the Harbor.

While further analysis is needed to tease out and refine these observations and their implications, it is again apparent that the time-varying GEV approach used here reveals which and to what extent various contributors are expressed from location to location. Establishing the climate covariability is a step forward in establishing future prognosis of extreme behavior via Global Climate-Circulation Models – will the future look like the past in terms of MSL and storm frequency variability? The climate indices used here, as well as the custom indices, indicates a spatial region, or fingerprint, indicative of physical forcing that factor into a local extreme climatology. For instance, the covarying regional forcing behavior could be examined under global climate models (GCM) forced by Representative Concentration Pathways (RCP) for greenhouse gas emissions and associated thermal warming to see if the forcing variance deviates from its historic envelop, which can be directly translated into an extreme water level response locally. Also, additional work is needed to explore and establish the applicability of customized climate indices. Similar to the above, the footprint of the custom indices could be examined in GCM's for changes beyond the historically observed trends (that might translate to important EVA-based responses at the study location). Such an effort will assist in developing prognosis of extreme event probabilities from GCM output tuned to variability/trends present within the footprint region.

In addition to the diagnosis plots, another set of figures was developed to help characterize the nature of the historical extremes distribution at each location (Figures 10a and 10b). In both of these figures, the top graph shows the daily 50-year return level with location and scale parameter contributions (i.e., the interannual cycle).¹ Here note how the expression of extremes differs between Guam (Figure 10a) and Honolulu (Figure 10b) over the year, with Honolulu exhibiting marked seasonality.

The middle graph in both figures shows the summer, winter and annualized 50-yr return level with long term tidal cycle and trend contributors. Here note how the expression of extremes differs between Guam (Figure 10a) and Honolulu (Figure 10b) over time as function of both the long term tidal cycle and the mean sea level trend, with Guam exhibiting marked interannual tidal variability.

In both figures the bottom graph shows the return level interval curves for year 2011 by season respective to tidal and trend value contributions. Here, note the two-fold difference in spread in magnitude between the low and high ends of the return intervals between the two stations, with Guam (Figure 10a) showing about a 20cm spread. These exceedance probability plots are in a form that is typically used to support engineering siting and design analysis. Note that those shown here go beyond what is regarded as standard practice in that they capture current conditions in a way that includes the response to time-specific tidal phase and the historical trend to create a more accurate estimate of the 'present day' exceedance probability.

Recognizing the purpose of this report is not so much to comment on results per se, as it is implications of results in the context of the successfully accomplishing the objectives of the

¹ *The likelihood of occurrence of unusually high (or low) sea levels commonly expressed in terms of a return interval or "Average Recurrence Interval" (ARI) or an Annual Exceedance Probability (AEP). Stephens, 2012.*

project and future work, the differences between Guam and Honolulu results evident in Figures 10a and 10b respectively highlight how the time-varying GEV approach used here helps to detect location to location differences in the character of the extremes distribution. It shows how such information can be used to formulate readily applicable products that can be used to describe the characteristics of the stationary extremes distribution - the Current Extreme Event Probability. The proof-of-concept forecast products discussed below, and based on novel methods developed through this project, go even further. They show how these methods can be used to formulate readily applicable products that describe how the characteristics of the extremes distribution might change with time as a result of both patterns and trends – incorporating Modes of

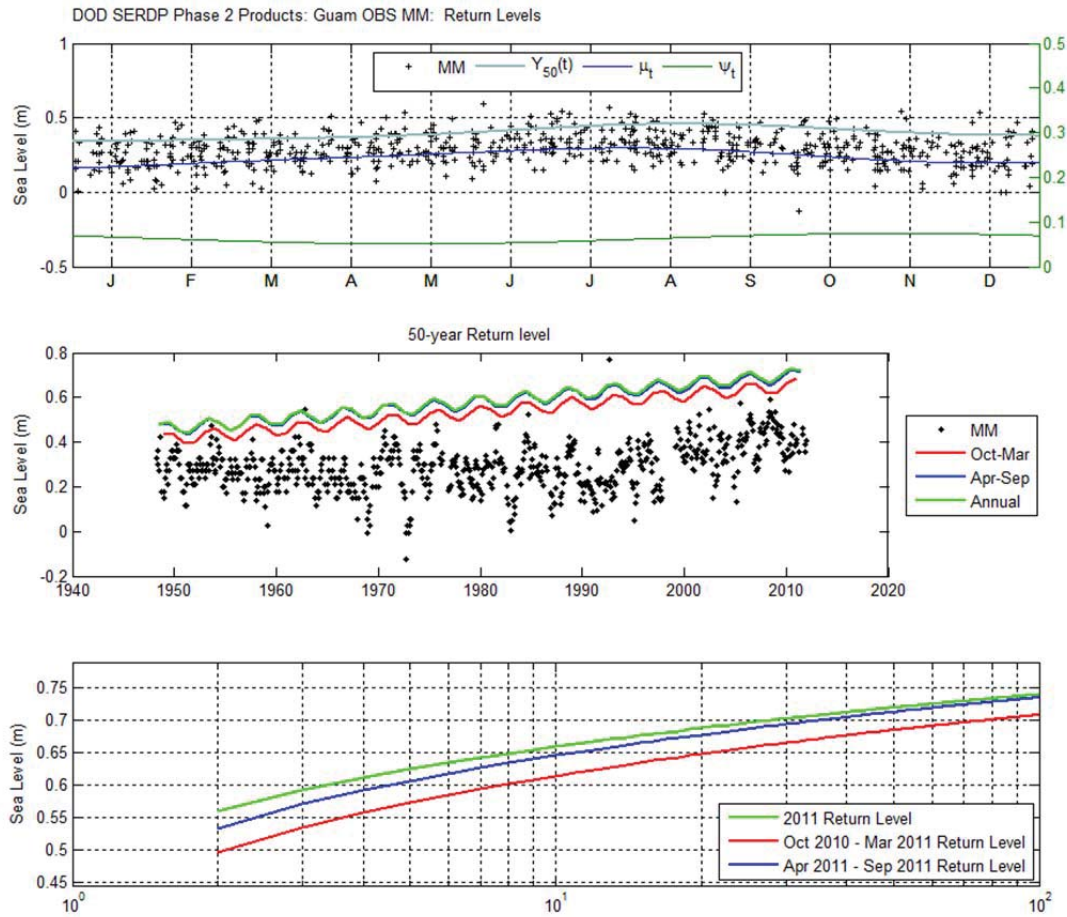


Figure 10a. Hindcast Product Sets for Guam. *Top: Daily 50-year return level with location and scale parameter contributions as three lines - the 50-year return period quantile within a year (light blue line), the time-dependent location parameter (blue line), and the time-dependent scale parameter (green line). The crosses are the monthly maxima. Middle: Summer (blue), Winter (red) and Annualized (green) 50-yr return level with tide and trend contributors. The observed time series of monthly maximum are shown in black (points). Bottom: Return Level Interval Curves for year 2011 by season respective to tidal and trend value contributions with the 2011 return level in green), October 2010-March 2011 return level in red, and April 2011-September 2011 return level in blue. See text for details.*

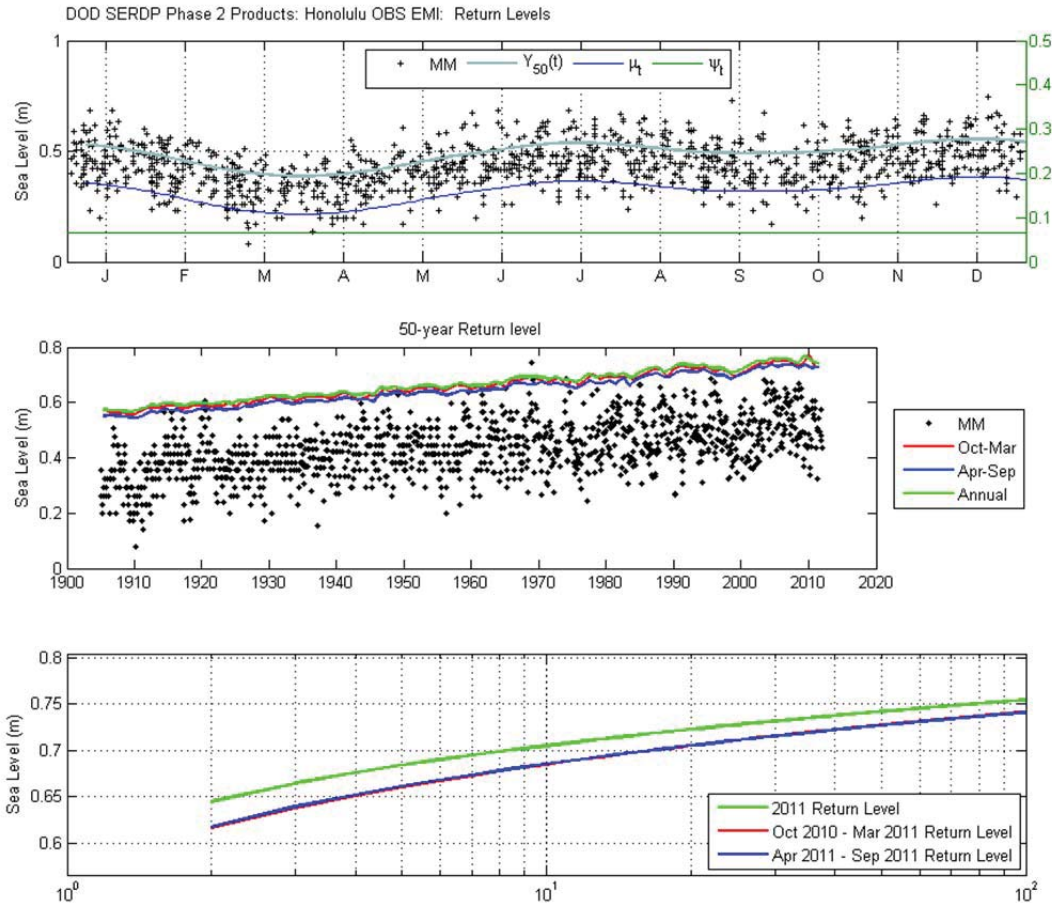


Figure 10b. Hindcast Product Sets for Honolulu. *Top: Daily 50-year return level with location and scale parameter contributions as three lines - the 50-year return period quantile within a year (light blue line), the time-dependent location parameter (blue line), and the time-dependent scale parameter (green line). The crosses are the monthly maxima. Middle: Summer (blue), Winter (red) and Annualized (green) 50-yr return level with tide and trend contributors. The observed time series of monthly maximum are shown in black (points). Bottom: Return Level Interval Curves for year 2011 by season respective to tidal and trend value contributions with the 2011 return level in green), October 2010-March 2011 return level in red, and April 2011-September 2011 return level in blue. See text for details.*

Variability and Future Sea Level Rise Scenarios. These concepts are considered in detail within the Guidance document that accompanies this work.

Figures 11a and 11b show three types of proof-of-concept forecast products created through the approach developed here to extend the potential applicability of time-varying GEV analysis to support decision-making. In both Figures 11a and 11b, the top graph shows the projected change in the 100-year return level with the long term tidal contribution over time for the current rate of SLR versus projected accelerated rates of 0.5m and 1.2m by 2100 (Intermediate Low and Intermediate High scenarios given by Parris et al., 2012, respectively). In the Guam plot (Figure

11a) note the overlap between the current rate of SLR and the Intermediate Low scenario. Also note, the long-term trend of the location parameter is based upon 60+ years of data and does not account for the recent multi-decadal sea level rise rate increase in the Western Equatorial Pacific. Changes in storminess are identified in the scale parameter or in the case of Guam where a long-term fit for the location parameter does not account for recent SLR acceleration so that the monthly maximum increasing push to higher bounds mimics increased storminess, or more aptly, an increased spread in the extreme distribution. Thus the “hindcast projected trend (based upon

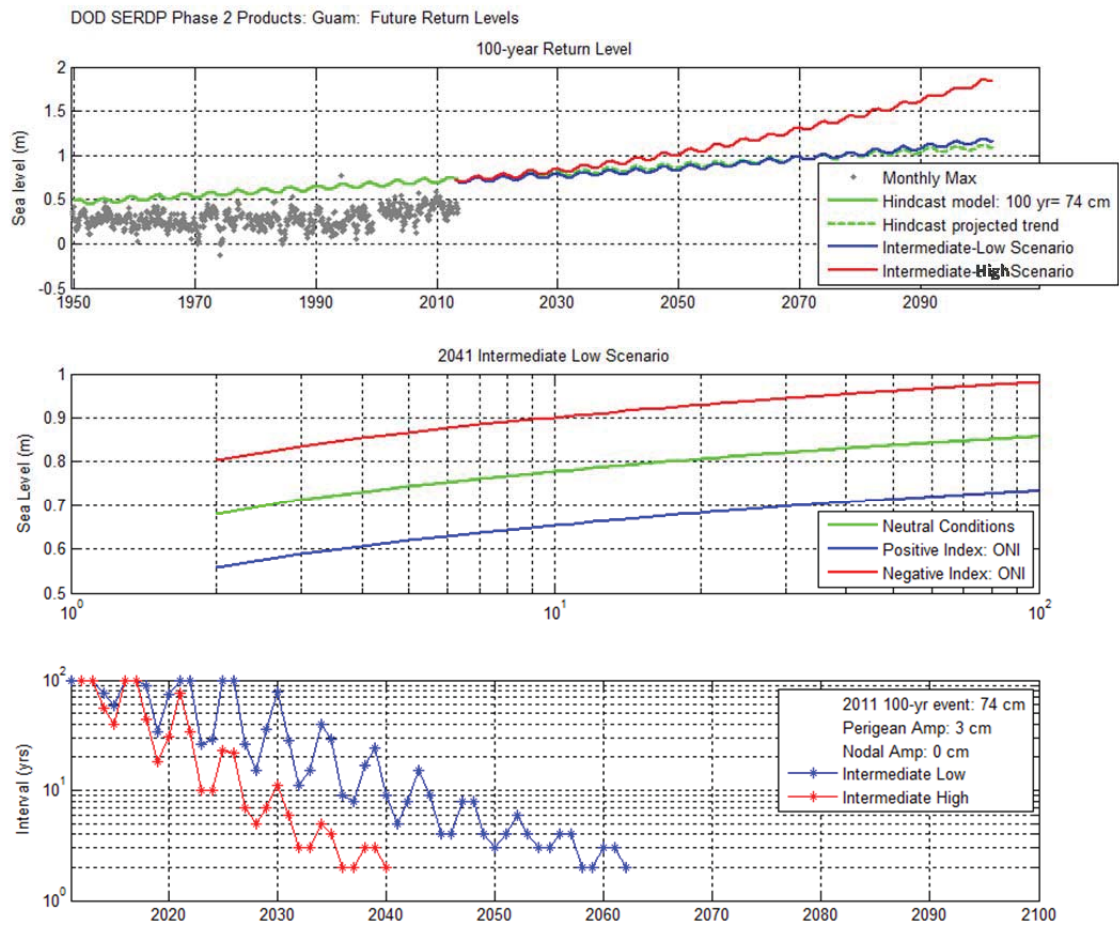


Figure 11a. Forecast Product Sets for Guam. *Top: Projected 100-yr return level with tidal contribution and three different SLR scenarios – the observed trend is in green and projected trends under intermediate high and low scenarios of Parris et al., 2012 are in blue and red respectively. Middle: Projected 100-yr return level for the year 2041 under ‘positive’ phase (blue), ‘neutral’ (green), and ‘negative’ (red) climate conditions – ONI. Bottom: Projected frequency “decay curve” of the elevation associated with the 2011 100-year return level with the tidal contribution for intermediate high (red) and low (blue) scenarios of Parris et al., 2012. See text for details.*

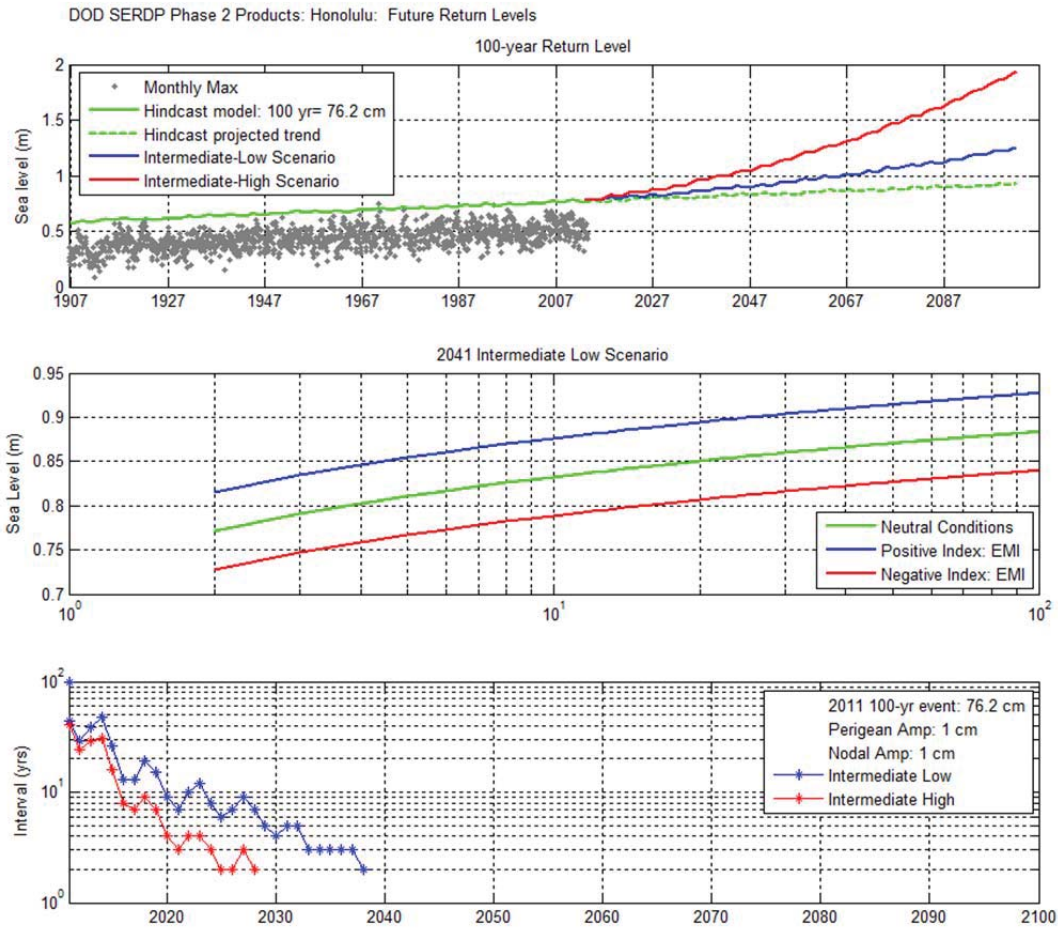


Figure 11b. Forecast Product Sets for Honolulu. *Top: Projected 100-yr return level with tidal contribution and three different SLR scenarios – the observed trend is in green and projected trends under intermediate high and low scenarios of Parris et al., 2012 are in blue and red respectively. Middle: Projected 100-yr return level for the year 2041 under ‘positive’ phase (blue), ‘neutral’ (green), and ‘negative’ (red) climate conditions – EMI. Bottom: Projected frequency “decay curve” of the elevation associated with the 2011 100-year return level with the tidal contribution for intermediate high (red) and low (blue) scenarios of Parris et al., 2012. See text for details.*

long-term linear regression and ~ 2 mm/year”) shown as the green dash keeps pace with the blue “intermediate-low Scenario” which equates to approximately 5mm/year (0.5 m) of sea level rise by 2100. No one else has done this scale parameter investigation, which will be of importance in distinguishing responses from sea level rise and storminess as they manifest and affect estimations of future return level curves. Investigation of trends and covariability of the scale parameter is ongoing. This effort will further distinguish contributions of the location and scale parameter to isolate low frequency MSL related changes (i.e., location parameter) from storminess (e.g., storm-track cycles/trends revealed in scale parameter) that is important for characterizing locations patterns of historic extreme vulnerability.

Note that the relationship used to create this plot can be solved for any return interval and any SLR curve. Also it can be solved for any time slice, thereby generating a version of the standard return-level curve (bottom plot in Figure 10a and 10b) for any year in the future. Taking this a step further, the middle graph in Figures 11a and 11b shows the 100-year return level for the year 2041 under ‘positive’, ‘neutral’, and ‘negative’ phase climate conditions. These plots highlight the ability to quantify the variation in return levels as a function of climate variability (e.g., ‘positive’ and ‘negative’ phases, blue and red respectively associated with any given climate index). The spread about the “neutral” condition varies depending on the given climate index and its expression at the given location. In some ways it is analogous to an error bar on the various curves in the top figure. This plot is based on information gained through the historical diagnosis. While it is not possible to determine the phase of the climate in the future (e.g., 2041), using this approach it is possible to account for its potential impact on the extremes distribution at any given time in the future – above or below the projected neutral condition. This is an important consideration and demonstrates the power of the approach to fine tune estimates or this sort that are needed for engineering and modeling applications.

The bottom graph in Figures 11a and 11b show the frequency “decay curves” of the elevation associated with the 2011 100-year return level with long term tidal contribution under the NCA Intermediate Low and Intermediate High scenarios of Parris, et al., (2012). They are in essence the inverse of the top plots in Figures 11a and 11b. They show how the frequency of a given return level elevation changes over time (versus how the elevation of a given frequency changes over time). The elevation selected here, to illustrate the concept, is that associated with the current (2011) 100-year return interval. The plot shows the time it takes (in years) for the this same elevation to transition down to that associated with the 10 or 2 year return interval, for example, under the different SLR scenarios. At Guam (Figure 11a) the soonest the elevation currently associated with the 100-year return interval becomes associated with the 2-year return interval is 2040. At Honolulu (Figure 11b) the comparable change has occurred well before then under both scenarios. Note that the rate of the decay is mostly associated with the “steepness” or slope of the return interval curve and is a function of the scale parameter since the shape parameters are all less than zero (indicating more convex curvature). As above, plots like this can be generated for any combination of starting elevation and SLR scenario.

While not completely novel (e.g., Hunter, 2010; Park et al., 2011; Tebaldi et al., 2012; Sweet et al., 2013) this is a particularly interesting use of the approach and is believed to have considerable practical applications. For example, with respect to site-specific applications one can imagine the starting elevation being that of a road, runway or similar such critical infrastructure. Given an understanding of the ‘functional integrity’ of such infrastructure – How many times or for how long can inundation occur before it can no longer function as intended? – one can use the type of information shown here to get a sense of what time that infrastructure may be rendered non-functional and then plan accordingly. The same sort of analysis can be applied to an assessment of ecosystem function. For example, at what point in time is a protective wetland no longer functional?

With respect to area-wide applications, Figure 12 shows the results of the frequency decay analysis –when the 100-year return interval becomes associated with 2-year return interval– for all Pacific Islands stations for the NCA scenarios (of Parris et al., 2012). Under the Intermediate

Low scenario for example, Kwajalein experiences this transition as early as 2030, Guam in 2060, and Midway as late as 2080. Information such as this can be used for screening purposes, for example to identify which stations will feel the effects of sea level rise sooner than others and correspondingly which locations might first warrant attention with respect to identification and implementation of adaptation options. . These results are similar to those by Hunter (2012) recently highlighted in the IPCC (Church et al., 2013) who determined a factor (based upon the scale parameter) by which the frequency of sea levels exceeding a given height would be increased for a particular mean sea level rise. These results indicate that locations with a more

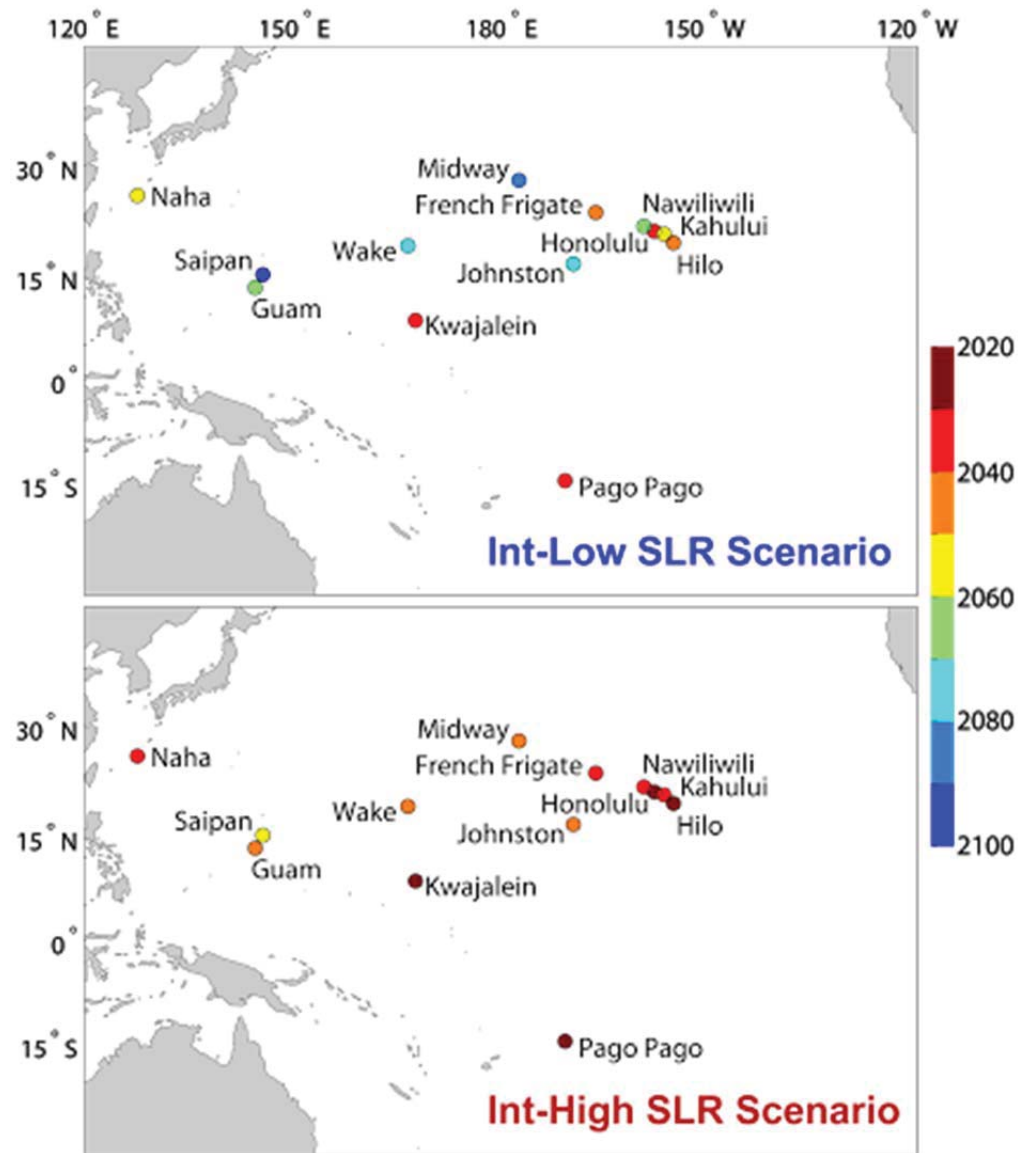


Figure 12. Decade in the future in which the elevation currently associated with 100-year return interval becomes associated with 2-year return interval, for each station based on the OBS runs. Top plot is for the NCA Intermediate Low Scenario and bottom plot for the Intermediate High Scenario of Parris et al., 2012. Decade for each station is identified by color bar on the right. See text for details.

tightly-bound extreme distribution (i.e., smaller scale parameter) will experience a greater change in event probability for a given return level.

The frequency decay analysis and related derivatives (e.g., integrated risk curves [communication with Dr. Obeysekera] and expected number of events over a given time horizon [Kopp et al., 2014]) serve to highlight an area identified as a priority for future work. Namely, focusing the applied research on the “lesser extremes” (i.e., <5 yr event probabilities) in the region encompassing the (high probability event) end of the return level curve and extending beyond analysis of “extremes” to include the entire water level distribution of daily maximums as to include more normal events. This will enable products like the decay curves to be taken down to achieve a finer level of granularity with respect to flood frequency, magnitude and most importantly, duration – from major flooding that occurs every few decades or years to minor flooding that occurs every few months or weeks. This will provide information about chronic events whose frequency is expected to increase dramatically with rising sea levels. Noting here the recent work of Merrifield et al., (2013), who quantify geographic variation in annual maximum water levels from tide station records across the globe and Sweet et al., (2014) on frequency and duration of cumulative impacts associated with lesser extremes across the U.S., this issue is considered further below. Also relevant in this context will be exploring and quantifying the concept of ‘functional’ integrity, via frequency-magnitude-duration thresholds or tipping-points for example, specific to individual assets of interest.

Finally, such information will need to be placed within an Information Technology (IT)-based decision-support system as a means to easily conduct “what if” scenario types of analyses. In this regard, efforts related to bridging science and information technology should be noted. These include the development of Geographic Information System (GIS)-based and other IT-based tools to support natural hazards-related decision-making (e.g., Gomez and Marra, 2002; Marra et al., 2005; Haddad et al., 2005; Marra et al., 2009; Kruk et al., 2013), and most recently efforts to aggregate and customize content to support location and sector-specific situational awareness in a web-based ‘dashboard’ environment. These pathfinding activities, which includes the work carried out as part of this project, build upon various national and regional efforts of the National Oceanic and Atmospheric Administration (NOAA), the United States Geological Survey (USGS), and the United States Army Corps of Engineers (USACE), among others working in various ways to foster community and ecosystem resilience to the impacts of sea level rise, coastal inundation, and extreme weather. Continuation of these activities will result in significant contributions to these important federal agency efforts.

Best-practices Guidance: The previous sections focused on the analysis and products resulting from this analysis. While useful outcomes of this effort in their own right, this work also contributed to the development of guidance that can be used to formulate probabilistic estimates of extreme events under a changing climate for specific locations in the Pacific Islands and beyond – a primary goal of this effort, with the Practitioners Guidance a separate, stand-alone document that accompanies this report as the specific outcome.

The guidance is focused on providing practitioners with an overview of concepts and consideration – help them understand how to frame the problem, assess their specific situation, identify the types of analyses that may be warranted (e.g., area-wide screening level vs. detailed

site-specific design analysis), and where to find information on details of the various types of analysis. It is not intended to provide details with respect to specific types of analyses and how to conduct them, as this can be found elsewhere. For example, methods for conducting the particular form of non-stationary extreme value analysis discussed in this report.

Embedded within an investigation framework (Figure 13), the guidance is grounded in the notion that for a given setting the “best” approach to the formulation of probabilistic estimates of extreme events under a changing climate depends on a number of factors, including both

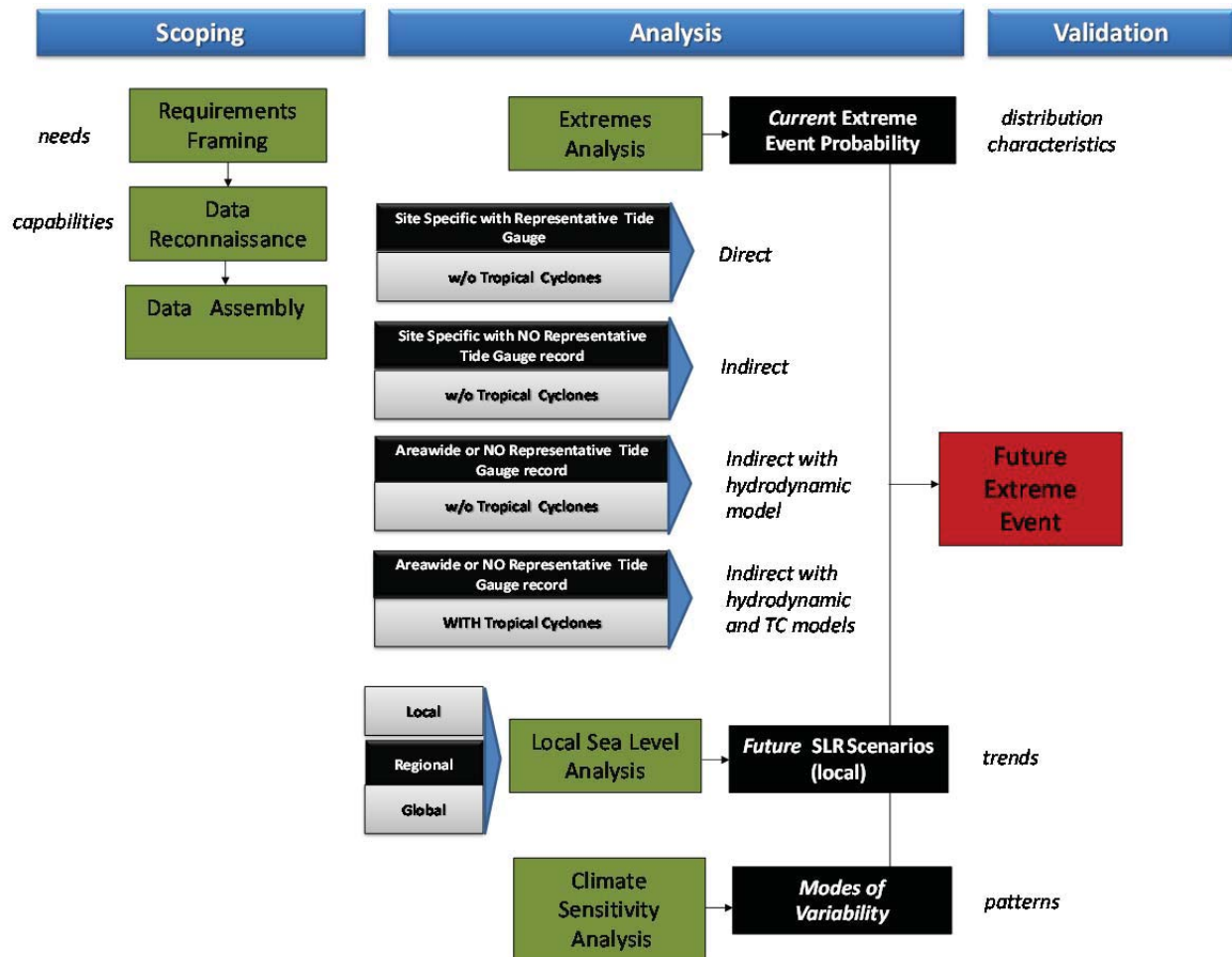


Figure 13. A framework for the formulation of probabilistic estimates of sea level extremes under a changing climate. The framework depicts a flow from scoping, through analysis, to validation. Scoping is required to assess needs and capabilities, and to a considerable degree determine which among a set of EVA methods may be most appropriate to use to estimate the stationary extreme event probability (e.g., direct, indirect, or hybrid). Local Sea Level Trend Analysis and Climate Sensitivity Analysis are required to assess the extent to which the characteristics of the extremes distribution might change with time as a result of both patterns and trends. Information from all three sets of analyses is combined to create products that inform decision-makers about Future Extreme Events and which are subject to validation prior and subsequent to their application. See accompanying Guidance document for details.

technical and practical considerations. The various elements of this framework fall under the headings of *scoping*, *analysis*, and *validation*.

Scoping is the foundation of the framework. To be carried out prior to data treatment and analysis, it involves an assessment of needs and capabilities via requirements framing, data reconnaissance, and data assembly respectively. A series of questions are posed to help practitioners identify relevant technical and practical considerations.

Analysis is the complex core of the framework. Elements include *Extremes Analysis*, *Local Sea Level Trend Analysis*, and *Climate Sensitivity Analysis*. Under the first element, EVA and other statistical methods that can be used to describe the characteristics of the stationary extremes distribution - the Current Extreme Event Probability - are introduced and discussed. Answers to the questions posed during scoping are used to establish a set of ‘cases’ and associated best practices statistical methods. Analyses encompassed within the cases build in complexity, both in terms of computational and data needs. They describe idealized situations as a way to introduce the various techniques for assessing extreme event likelihoods and help understand their respective strengths and weaknesses in the context of potential requirements and resources combinations.

Under the latter two elements, attention is given to methods that can be used to describe how the characteristics of the extremes distribution might change with time as a result of both patterns and trends – Modes of Variability and Future Sea Level Rises Scenarios, respectively. With this information in hand, ways in which the results of the various analyses can be combined to create estimates of Future Extreme Event likelihood in forms amenable to decision-making are then explored. Validation is carried out subsequent to analysis. Activities such as ground-truthing and monitoring of indicators and impacts are identified to ensure that attention is given to an evaluation of the accuracy of results prior to their application.

Discussions during the technical workshop also raised a series of reoccurring issues applicable to EVA generally and that came to be referred to as the “tale of two tails”. While nuanced, to a considerable extent this issue centered on the nature of the distribution shape (i.e., Weibull, Gumbel, and Frechet) and the extent to which various methods are able to accurately reflect this. It was noted that there has been a tendency to focus on the more rare (i.e., high magnitude/low probability) catastrophic events that make up the upper tail of the extremes distribution. In many locations these “greater” extreme events are closely associated with tropical cyclones, yet their low likelihood of being captured in tide station records (even over long time spans) means their probabilities are not accurately predicted. This issue is being addressed with respect to the estimation of current extremes (e.g., McInnes et al., 2009; Grinstead et al., 2013; Haigh et al., 2013b). However, it remains a challenge to assess how the magnitude and frequency of the greater extreme water level events might change with a changing climate because expected changes in tropical cyclone characteristics under a changing climate yield conflicting results (e.g., ABOM/CSIRO, 2011; IPCC, 2013). Simulations to date suggest little to no significant long term change in the upper tail of the extremes distribution for locations where TCs are prominent feature (e.g., Colberg and McInnes, 2012; Haigh et al., 2013b).

It was also noted that greater attention is starting to be given to the more common (i.e., low magnitude/high probability) chronic events that makeup the lower tail of the extremes

distribution. Such events are commonly associated with extreme tides. Such “lesser” extreme events are well represented in tide station records, and as a result their potential magnitude and frequency of occurrence accurately predicted.

Also, because expected changes the magnitude and frequency of the lesser extreme water level events is closely linked to changes in mean sea level change, there is greater ability to assess how the lower tail of the extremes distribution will change with a changing climate. Most importantly, lesser extremes are likely to have the greatest cumulative impacts to social, economic, and environmental assets over the coming decades, as in many locations their frequency will increase dramatically with rising sea levels (e.g., Firing and Merrifield, 2004; McInnes et al., 2011; Sweet et al., 2014; Sweet and Park, 2014). As a result, delineating the expression of these so-called lesser extremes in a changing climate is targeted as an area of future research and follow-on applications development.

Conclusions and Implications for Future Research

The overall objective was successfully achieved. The results have advanced the practical application of extreme value analysis to inform decision and policy making as well as our basic understanding of the factors affecting SLR and coastal inundation. Methods were developed to create innovative proof-of-concept products that can be used directly to support decision-making ranging from area-wide vulnerability assessment related to climate adaptation planning and disaster risk reduction to site-specific analysis related to design and maintenance of facilities and infrastructure at select DoD sites. Development of these methods, along with a review of previous work and expert input on best practices, formed the basis for the creation of guidance that can be used to formulate probabilistic estimates of extreme events under a changing climate for specific locations in the Pacific Islands and beyond. These efforts have served to identify issues and opportunities for future work.

With respect to specific objectives related to both the basic and applied nature of the research:

- The time varying EVA methods used here were able to detect how various contributors – patterns of sea level variability and storminess as well as global and regional trends – have uniquely combined to determine extreme water levels at specific locations. These historical diagnoses of a location’s extreme response were applied in a novel manner to create a set of innovative tide station-based proof-of concept forecast products that help explain how extremes might be expected to change in a changing climate. This approach will facilitate further prognosis as Global Climate Models outputs become validated and their outputs are linked to the various contributors to extreme water levels.
- We examined seasonal and defined tidal cycles, covariability patterns, and long term trends in location and scale parameters, though focused in more details on the location parameter (i.e., did not investigate covariability in scale). The results confirm work of previous investigators which suggest that there is considerable variation from location to location with respect to which and to what extent various contributors are expressed, and that trends in extreme levels tend to follow trends in MSL.
 - On a station by station basis, areas typically experiencing greater water level setup events (e.g., due to topobathymetric effects) have higher location parameters; those with more energetic environments have steeper return interval curves (larger scale parameter) and those experiencing rare (e.g., tropical cyclones) have larger shape parameters.
 - For most locations, the seasonal variability governs the bulk of the time-varying variance in the extreme distribution but this is expressed on an intra-annual basis.
 - For some locations, low frequency (climate variability) is an important time-varying contribution to mean sea level, affecting extreme probabilities on the same order as the effect of the seasonal cycle (e.g., Guam, Kwajelin Saipan).
 - A few locations (e.g., Hawaiian Islands and Midway) were found to have significant covariability with unique forcings (i.e., Hawaiian Islands sensitivity to SLP within a spatial footprint and Midway’s atoll which experiences substantial wave setup from the regional the wave field).
 - In all cases, there were substantial long-term trends associated with changing relative sea levels.

- A few stations (i.e., French Frigate and Honolulu) had minor trends in the monthly max water level series above the MSL trend.

Investigation of trends and covariability of the scale parameter is ongoing. This effort will further distinguish contributions of the location and scale parameter to isolate low frequency MSL related changes (location parameter) from storminess patterns (e.g., storm-track cycles/trends revealed in scale parameter) that is important for characterizing patterns of historic extreme vulnerability. For instance, it is known that during El Niño episodes mean sea level is elevated over much of the U.S. West Coast (Sweet and Park, 2014). However, storm tracks are also typically affected by the position of the jet stream which varies according to phases of ENSO, which has been shown to affect storm-surge frequency along the U.S. East Coast (Sweet and Zervas, 2011; Thompson et al., 2013). Additional work is needed to explore and establish the applicability of customized climate indices. This effort will assist in developing prognosis of extreme event probabilities tuned to variability/trends present within the footprint region from GCM output.

- Development and application of the time varying EVA methods used here, along with a review of previous work and expert input on best practices, suggests that the “best” approach to formulate probabilistic estimates of extreme events under a changing climate for a given location is dependent on a number of factors. Requirements framing and data reconnaissance are part of the scoping that is essential prior to analysis. Once such scoping has been carried out there are several ways through which to proceed to determine the current extreme event probability. In all cases, both climate sensitivity and sea level trend analysis needs to be conducted to determine future extreme event probabilities.
- There has been a tendency to focus on rare (i.e., high magnitude/low probability) inundation events. The behavior of more common (i.e., low magnitude/high probability) inundation events have recently begun to receive attention. These “lesser” extremes are likely to have the greatest cumulative impacts over the coming decades, as in many locations their frequency will increase dramatically with rising sea levels levels (e.g., Firing and Merrifield, 2004; McInnes et al., 2009 a; McInnes et al., 2009b). As a result, delineating the expression of these so-called lesser extremes in a changing climate is targeted as an area of future research and follow-on applications development. Of particular interest is the identification and linkage of magnitude, frequency, duration trajectories to assets of concern, and the contextualization of this information within an IT-based decision-support application environment.

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Appendix A: Hindcast and Forecast Products and Product-specific Guidance

readme.txt

The RC2335_Products Folder contains the following:

- Product-specific Methodology Document
- Hindcast Products Folder
- Forecast Products Folder

Product-specific Methodology Document

This document outlines the analysis procedure used to create the products that can be found in the Hindcast and Products Folders. It also provides a detailed description of the products in these folders.

Hindcast Products Folder

This folder contains

- An excel file titled Phase2_RESULTS.xlsx, with the results of all 6 GEV OBS runs at each of 15 tide stations (by climate parameter and by station). Each station has a separate sheet, which include the terms and standard error for the location, scale and shape parameters. The amplitudes and percent variances for each significant term is also included for each station.
- Figure AH1. Hindcast Analysis: Return Level Results (in the form of .png files) for each of the 6 runs and for each of the 15 stations (station#_climate indice_RL.png) , which consists of three separate plots.
- Figure AH2 Hindcast Analysis: Contributions to the Location Parameter (in the form of .png files) for each of the 6 runs and for each of the 15 stations (station#_climate indice_mu.png). If the model allows for a time-dependent scale parameter, the contributions to the scale parameter are shown in a third figure (station#_climate indice_psi.png).

Forecast Products Folder

This folder contains

- Figure AF1. Forecast Analysis: Return Level Results (in the form of .png files) for each of each of the 15 stations (station#_Projected_RL.png) , which consists of three separate plots.

Appendix B: Research Plan

This document outlines areas where future research and follow-on applications development is warranted, based on insights gained through activities conducted as part of the Limited Scope Project - Advancing Best Practices for the Formulation of Localized Sea Level Rise/Coastal Inundation "Extremes" Scenarios for Military Installations in the Pacific Islands (RC-2335). Activities described in the Limited Scope Report (LSR) that accompanies this document include an extensive round of Extreme Value Analysis (EVA) on Pacific Island tide station records, a technical workshop involving presentations and discussion among experts from across the globe, and a broad review and synthesis of existing literature.

Area 1. Continue the Historical Diagnosis of Location-Specific Sea Level Patterns and Trends. Results to date confirm that there is considerable variation from location to location with respect to which and to what extent various contributors are expressed. However, as noted in the LSR, further analysis is needed to tease out and refine these observations and their implications. In this regard, several aspects of the historical diagnosis of location-specific sea level patterns and trends are highlighted.

Task

- 1.1 **Conduct further sensitivity analysis with respect to the expression of location, scale, shape parameters within tide station records using observed and nontidal residual information.** Additional work is needed to decipher the differences in location and scale parameters to further isolate low frequency MSL related changes from changes associated with storminess phases (e.g., storm-track cycles/trends) in order to better characterize a location's extremes vulnerability in light of a changing climate and ultimately support scenario development. Findings based upon observed storm tides (tides and nontidal residual combined) from our LSR have noted important climatic covariability in the extreme distribution's location parameter indicating more prolonged changes associated with mean sea level variability such as those that occur during phases of ENSO. In regions of the Western Equatorial Pacific where recent sea level rise has been increasing rapidly over the last couple decades (e.g., Guam likely from forcing associated with the Pacific Decadal Oscillation [PDO]), the persistent elevation of all monthly maximum has mimicked an increase in extreme variability. The change has been quantified in terms of a trend in the scale parameter but might be tuned as a covariate instead. Allowing for covariability in the scale parameter will help decipher changes in the extreme distribution associated with changes in the mean versus changes in variance that might result from changing storm track tendencies (e.g., increased U.S. East Coast storm surge frequency during El Niño). Comparisons should be made between time-varying location and scale parameter methods using nontidal residual and observed water levels as the latter has the joint-probability of the tide phase inherent to its results. The end result of a time-varying location/scale investigation should further refine frequency factor coefficients under MSL rise estimates of Hunter 2012 as well as provide "climatic envelopes" of extreme probability potential. Note that investigation of trends and co-variability of the scale parameter by members of the project team is ongoing.

Investigators: Current Project Team

Timeline: Year 1 - Investigate trends and covariability of the scale parameter

Task

- 1.2 Explore and establish the applicability of customized climate indices and establish future estimates tuning covariate sensitivity to GCMs output.** Additional work is needed to identify customized indices via their co-variability with characteristics of the extremes distribution. This will assist in developing prognosis of extreme event probabilities, for example by using GCM output tuned to variability/trends present within the footprint region of the custom indices. In our LSR effort, we successfully demonstrated that the extreme water level distribution throughout the Hawaiian Islands is highly sensitive to sea level pressure (SLP) variability over the last 6 decades. Others have used custom indices to highlight important covariability and linked the findings to GCM output to provide future guidance. For instance, Grinsted et al., 2012, 2013 showed that a regional hurricane storm-surge index showed sensitivity in a time-varying GEV parameter to covariability in GCM global and regional temperature patterns to deduce that a doubling of Katrina magnitude events would occur associated with the warming over the 20th century. Ultimately it will support scenario development.

Investigators: Current Project Team

Timeline: Year 1 - Identify customized indices

Year 2 - Link indices to GCM output

Task

- 1.3 Delineate still water from wave-forced responses in the tide station-based extreme model.** A systematic review of the tide station water levels and near shore wave observations or validated models together with the time-varying GEV approach used here would help to quantify contributions of the wave field inherent within the tide gauge record. For instance, we have shown that the extreme distribution at the Midway tide gauge, whose daily observations had previously been shown to be sensitive to wave setup due to its tide gauge atoll location (Aucan et al., 2012) covaries with significant wave height reanalysis data from the Global Ocean Wave (GOW) model. Analysis of intra-annual (i.e., seasonal) varying estimates of the location and scale parameter without usage of the covariate showed the location parameter varied in phase with the MSL cycle and that the scale parameter varied in phase with the ocean wave climate (not shown). When used as a covariate, the GOW index explained >90% of the variance in the location parameter. Preliminary analysis at other Pacific sites shows that there are other locations with a much lesser, but still significant amount of variance attributed to regional wave forcing. The time varying technique might successfully be used to normalize the variance imparted by waves to arrive at a more genuine still water measurement. To our knowledge, this type of analysis has not previously been performed using tide gauge observations and is important to help distinguish the effects of tide gauge placement (i.e., exposed ocean such as in La Jolla, CA, atoll in Midway, south-facing harbor of Honolulu, north-facing harbor of Hilo, etc.). Note that investigation of wave-forced responses in the tide station records by members of the project team is ongoing.

Investigators: Current Project Team with Additional Partners

Timeline: Year 1 - Review of the tide gauge water levels and wave observations

Area 2. Delineate the expression of “lesser extremes” (<5 year event probabilities) in a changing climate and contextualize this information within an IT-based decision-support application environment. As noted in the LSR, more common (low magnitude/high probability) minor flooding events that makeup the lower tail of the extremes distribution are likely to have the greatest cumulative impacts to social, economic, and environmental assets over the coming decades, as in many locations their frequency will increase dramatically with rising sea levels. Recognizing the importance of addressing this concern, work in this area is identified as the emphasis for future research and follow-on applications development. Elements of applied research that leads to and includes the development of an operational decision-support system are summarized below.

Task

- 2.1 Explore and diagnose the behavior of lesser extremes in a changing climate.** This would involve the conduct of applied research and analysis connecting a location’s extreme value distribution to its fully represented probability distribution that includes lesser extremes. Part of the applied research will determine the distributions that provide the most robust probability estimate in this transition region. Upon satisfactory probability fitting, time-varying models would be applied to investigate climate sensitivity. It would also involve extending and linking this to the overall ‘total’ water level distribution so as to quantify the probabilities/project the likelihood of events, with an emphasis on those that are more chronic in nature.

As noted in the SLR, members of the project team have already commenced work of in this area. For example, the recent work of Merrifield et al., 2013, who quantify geographic variation in annual maximum water levels from tide station records across the globe and Sweet et al., 2014 who explore SLR impacts on the frequency of so-called nuisance flooding across the U.S. Sweet and Park 2014 recently showed that annual exceedance of nuisance flood events is sensitive to ENSO on both the U.S. East and West Coasts. Other investigators have been exploring techniques such as joint probability analysis of waves and water levels as a means to quantify the probabilities/project the likelihood of TWL events (not just SWL) which is critical to truly arrive at risk estimates for high wave/low storm surge environments like the Pacific region. For example, Serafin and Ruggiero 2014 use time varying methods to simulate the various components of TWLs (waves, tides, and nontidal residuals) taking into account conditional dependencies that exist between the various components.

Investigators: Current Project Team with Additional Partners

Timeline: **Year 1** - Statistical analysis of minor flooding events

Year 1 and 2 - Joint probability analysis of waves and water levels to project TWL, with an emphasis on lesser extremes.

Task

- 2.2 Establish frequency-magnitude-duration thresholds tied directly to assets of concern.**

This would involve research, including field studies needed to: a) catalog critical infrastructure and habitat; b) identify ‘inundation landmarks’ and establish the tipping points

with respect to the functional integrity of these assets in terms of their inundation sensitivity (e.g., magnitude, duration, frequency thresholds); and c) generate asset-specific inundation impact trajectories for a set of climate scenarios. This work would start with a select set of locations (e.g., Kwajelin, Hawaii, Guam). It would involve robust and sustained consultations with relevant stakeholders in each of these locations. In many ways the elevation analysis would be an analogous (but targeting particular infrastructure) to the location specific thresholds established in CONUS by the National Weather Service's minor (aka nuisance), moderate and major flood impact levels.

Investigators: Current Project Team with Additional Partners

Timeline: **Year 1** - Catalog critical infrastructure and habitat and identify 'inundation landmarks' for a select set of locations

Year 2 and 3 - Establish the tipping points with respect to the functional integrity and generate asset-specific inundation impact trajectories for a set of climate scenarios and/or sea level rise scenarios (e.g., Parris et al., 2012) or probabilistic projections (e.g., Kopp et al., 2014) for a select set of locations.

Task

- 2.3 **Develop and deploy an IT-based application to facilitate asset-specific inundation impact assessment and monitoring.** This would involve automation of the process used to generate asset-specific inundation impact trajectories noted above. It would also involve the aggregation of this information along with other relevant content that could be used to support situational awareness related to coastal flooding. Such 'dashboard's' could be tailored in terms of geographic coverage as well as time frame of interest. At decadal scales, they could include projected and actual asset-specific inundation impact trajectories. At annual to seasonal scales, in addition to event/impact monitoring and reporting they could include seasonal mean sea level anomaly (MSLA) and storminess outlooks. As part of an integrated climate early warning system they could also include real to near real time information as well as short-range forecasts.

The PI has experience and expertise bridging science and information technology, including the development of GIS-based and other IT-based tools to support natural hazards-related decision-making (e.g., Gomez and Marra, 2002; Marra et al., 2005; Haddad et al., 2005; Marra et al., 2009; Kruk et al., 2013), and most recently efforts to aggregate and customize content to support location and sector-specific situational awareness in a web-based 'dashboard' environment.

Note that plans are currently underway to commence counting the frequency of water level elevation events exceeding the NOAA NWS flood or other such locally relevant landmark elevation threshold (e.g., days and hours) for a select set of tide stations along the mid-Atlantic and Pacific Islands coasts. Based on an analysis of tide station water level climatology, counts would be compared to both "normals" for that period and the projected long term trend. These results (and other such statistics) will be summarized on a quarterly and annual basis in graphic and text-based formats. As part of this effort attention is being given to monitoring and reporting via regional or local dashboards, a number of which are

currently under development in various forms. Also note that the Pacific Disaster Center has considerable experience in this area.

Investigators: Current Project Team with Additional Partners

Timeline: **Year 1** – Monitor and reporting of minor flooding events dashboard.

Year 2 - Inundation outlook based on MSLA and storminess dashboard embedded within a climate early warning system.

Year 3 - Projected and actual asset-specific inundation impact trajectories dashboard.

Area 3. Explore application of the time-varying GEV methods used here to satellite altimetry (SSH) records. Potential limitations of GEV related to the sparseness of data are well known and are a particular concern in the Pacific Islands. This issue applies to both tide station and wave buoy data. Of particular interest here is conducting a series of activities to assess the extent which SSH data from the 20+ year record of the satellite altimeters is amenable to GEV and other statistical analysis, as a means to cover a broad geographic area and extend the analysis beyond SWL, at least for quantification of the probabilities of lesser extremes. In addition to exploring the applicability of the time-varying GEV methods used here to estimate extreme water levels, this would involve comparing and calibrating altimetry data with tide station and wave buoy data as part of an integrated, area-wide diagnosis of historical water level patterns and trends. Future research and follow-on applications development in this area is intended to extend the focus of work beyond station-based to area-wide analysis. In this regard, the initial goal will be to establish complete coverage of coastal areas within the region surrounding the Main Hawaiian Islands. Such work examining satellite altimeter for extreme event characterization of storm surge is just starting to be investigated as the data set nears 20 years in record. For instance, Chen et al., 2014 were able to use related tide gauge storm-surge estimates with those measured by with an opportunistic fly-over of a satellite altimetry to quantify the cross-shelf surge and forced-wave characteristics associated with Hurricane Sandy. On the other hand, Antony et al., 2014 used multiple altimeter tracks to investigated storm surge responses in the Bay of Bengal and found this useful for cross-shelf variations of storm surges for model validation. Elements of work in this area are outlined below.

Note that via recent communications between the project team, members of other SERDP project teams, as well as colleagues with in NOAA (Dr. Laury Miller and Dr. Eric Leuliette of NOAA NESDIS STAR and the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO), pathfinding activities in this area have commenced.

Investigators: Current Project Team with Additional Partners

Timeline: **Year 1** – Compare and calibrate altimetry data with tide station and wave buoy data to assess feasibility. Contingent upon results in:

Year 2 – Conduct an integrated area-wide diagnosis of historical water level patterns and trends of coastal areas within the region surrounding the Main Hawaiian Islands (MHI) using EVA and other methods of statistical analysis; and

Year 3 –Develop area-wide prognosis of the frequency and duration of lesser extremes in a changing climate for coastal areas within the MHI region.

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